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GEOLOGICAL REPORT GR81-1

VOLCANIC ROCKS OF THE FOX RIVER BELT, NORTHEASTERN MANITOBA

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Winnipeg,
1981

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MAP

MAP GR81-1-1 Geology of the Western Part of the Fox River Belt .... (in pocket)

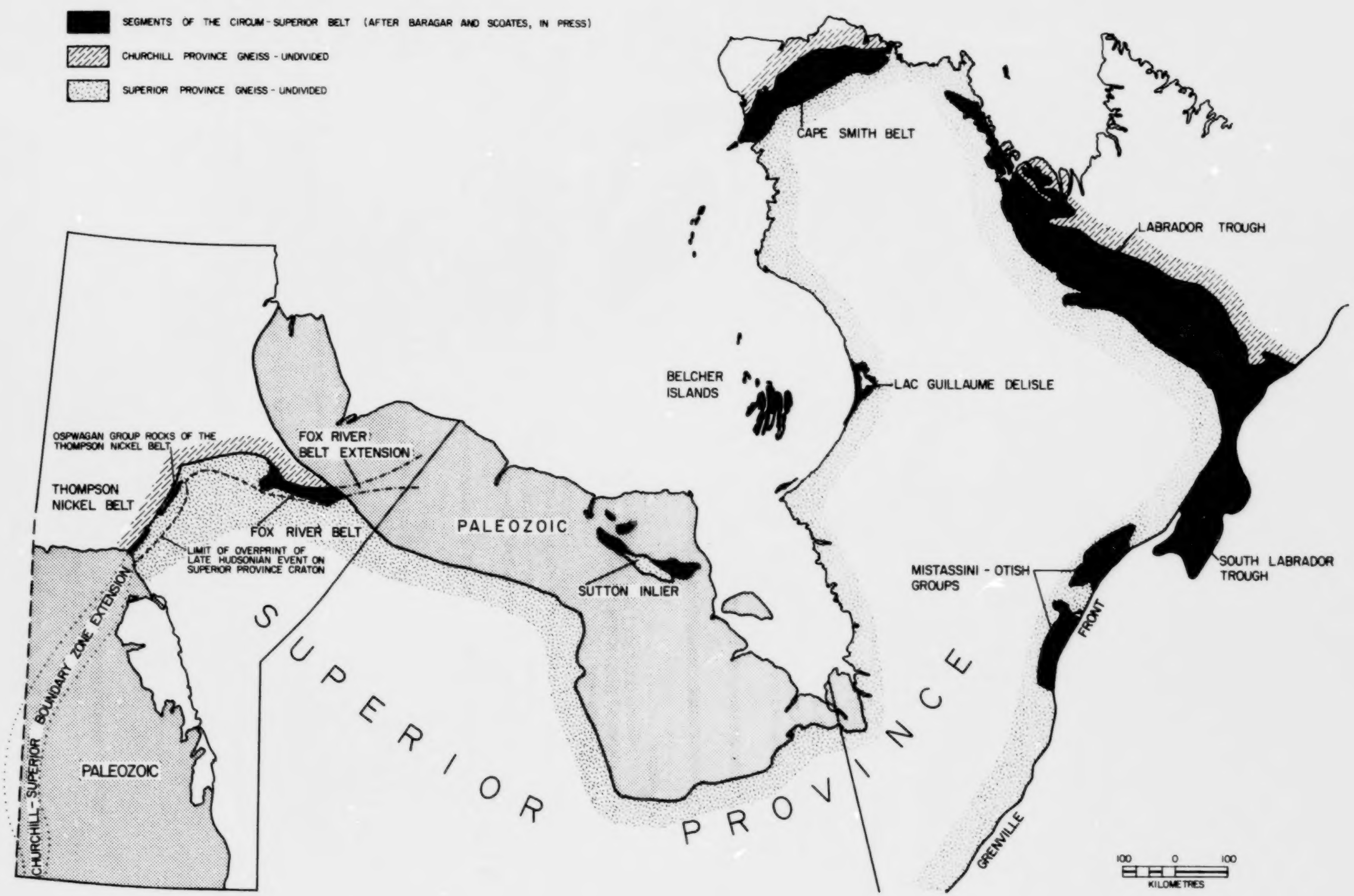

SEGMENTS OF THE CIRCUM-SUPERIOR BELT (AFTER BARAGAR AND SCOATES, IN PRESS)
CHURCHILL PROVINCE GNEISS - UNDIVIDED
SUPERIOR PROVINCE GNEISS - UNDIVIDED
CAPE SMITH BELT
LABRADOR TROUGH
BELCHER ISLANDS
LAC GUILLAUME DELISLE
OSPWAGAN GROUP ROCKS OF THE THOMPSON NICKEL BELT
FOX RIVER BELT EXTENSION
THOMPSON NICKEL BELT
FOX RIVER BELT
PALEOZOIC
LIMIT OF OVERPRINT OF LATE HUDSONIAN EVENT ON SUPERIOR PROVINCE CRATON
SUTTON INLIER
MISTASSINI - OTISH GROUPS
SOUTH LABRADOR TROUGH
CHURCHILL - SUPERIOR BOUNDARY ZONE EXTENSION
SUPERIOR PROVINCE
FRONT
GRENVILLE
PALEOZOIC
100 0 100
KILOMETRES

FIGURE 1: Relation of Fox River Belt to northern part of Circum-Superior Belt

INTRODUCTION

GENERAL GEOLOGICAL FEATURES

The Fox River Belt forms a segment of the Circum-Superior Belt (Baragar and Scoates, in press), a sequence of Proterozoic supracrustal rocks of broadly similar age, stratigraphy and lithologies that is unevenly distributed around the margin of the Archean Superior Province (Fig. 1). The Fox River Belt borders the northeast edge of the Superior Province craton in Manitoba for approximately 300 km, and forms a portion of the Churchill-Superior boundary zone. It consists of sedimentary rocks, large differentiated sills, and ultramafic to mafic volcanic rocks, which form a homoclinal sequence that is interpreted to have been deposited upon Superior Province gneiss. All of the outcrops and most of the diamond drill holes are west of the Stupart River, and east of the confluence of the Fox and Bigstone Rivers, a distance of approximately 50 km. Unless otherwise specified, the stratigraphy, thickness, and composition of units of the belt described in this report, refers to this area.

Sedimentary rocks occur in three stratigraphic positions (Table 1, Fig. 2) and consist of siltstone, argillite and shale interlayered with sandstone, quartzite and dolomite. Large concentrations of iron formation are interpreted, on the basis of aeromagnetic anomalies, as occurring in three widely separated areas of the Lower sedimentary formation. All sedimentary rocks are fine grained, and originally consisted of chiefly quartz, clay minerals and carbonate minerals. There is a distinct absence of lithic components.

Large differentiated sills have intruded the upper part of the Lower sedimentary formation, and the Fox River Sill has intruded the Middle sedimentary formation (Table 1, Fig. 2). The former range from 1.5 to 20 km long and average 800 m thick, and the latter forms western and eastern segments, each about 70 km long that are separated by a gap of 12 km. The thickness of the sill in the western segment is estimated to average 2 km at the present erosional surface. Distinctive aeromagnetic anomalies east of the eastern segment indicate that ultramafic rocks extend for another 100 km beneath cover rocks of the Hudson Bay Lowlands.

Volcanic rocks comprise approximately 40 percent of the rocks of the belt, and are intercalated with the sedimentary formations (Table 1, Fig. 2). They form two sequences referred to informally as the Lower and Upper volcanic formations, approximately 2 km and 3 km thick, respectively. The volcanic rocks form extensive sheets characteristic of fissure eruption, based on correlation of certain units over distances of 40 km. The volcanic rocks of the Fox River Belt have compositional equivalents in other segments of the Circum-Superior Belt, most notably in Ospwagan group volcanic rocks of the Thompson Nickel Belt and in the middle and upper divisions of tholeiitic and komatiitic basalt of the Cape Smith Belt. The volcanic rocks and differentiated intrusions of the Fox River Belt are part of a distinctive Aphebian magmatic suite that characterizes the northwestern part of the Superior Province craton in Manitoba (Scoates and Macek, 1978). The suite includes intrusive and extrusive mafic and ultramafic rocks of the Ospwagan group of the Thompson Nickel Belt (Scoates et al., 1977), and the mafic and ultramafic rocks of the Molson dyke swarm (Scoates and Macek, 1978).

Fox River Belt rocks have suffered low, to very low grade metamorphism. Pumpellyite and prehnite are indicator minerals in rocks of the Upper volcanic formation, and are absent from rocks in the upper and lower part of the Lower volcanic formation. Metamorphism increases from very low grade to low grade with stratigraphic depth. It is not known whether the metamorphism is due to burial or a low grade dynamothermal event.

AGE RELATIONSHIPS

The age of deposition of Fox River Belt rocks has not been unequivocally established. The relatively unmetamorphosed and undeformed rocks of the Fox River Belt contrast with the deformed and metamorphosed paragneiss of the adjacent Churchill Province (Scoates, 1977). This could be interpreted to indicate that Fox River Belt rocks were deposited after the peak metamorphism and deformation of the adjacent Churchill Province had been accomplished. Alternatively, it could be argued that the higher grade rocks of the Churchill Province were faulted against Fox River Belt rocks. In an attempt to resolve the problem of age of deposition of Fox River rocks, several Rb-Sr determinations have been made (Scoates and Clark, in prep.). A preliminary age of 1735 Ma has been obtained on Fox River komatiitic basalt and basalt. A preliminary age of 1720 Ma, previously reported as 1610 Ma by Weber and Scoates (1978), has been obtained from hornfelsed quartz-rich siltstone immediately adjacent to the south margin of the Fox River Sill. These ages are indistinguishable from a preliminary age of 1740 Ma obtained from Churchill Province paragneiss just north of the Fox River Belt. If the ages obtained from the komatiitic basalt and hornfelsed siltstone represent original ages of deposition and intrusion, respectively, then these original ages are indistinguishable from a metamorphic age of rocks that are juxtaposed. It thus seems reasonable to suggest that all these ages reflect readjustment of the Rb-Sr system in response to recrystallization of Fox River Belt rocks and adjacent Churchill Province paragneiss under low to very low grade metamorphic conditions, and that the deposition of all these rocks is older than the Rb-Sr ages obtained. Thus, although the relationship between the age of deposition of Fox River Belt rocks and the age of metamorphism of Churchill Province paragneiss is still unresolved, the deposition of Fox River Belt rocks and the metamorphism of the paragneiss are considered to have been accomplished before the Churchill and Superior provinces became juxtaposed.

Separating metamorphic-deformational events from depositional events is also a problem in other Circum-Superior Belt segments. The rocks of many segments possess an unconformable relationship with rocks of the Archean Superior Province craton and their deposition is consequently post-Kenoran. Many segments have undergone an Hudsonian overprint so that deposition within those segments is bracketed by the Archean, Kenoran event and the Proterozoic, Hudsonian event. Interpreted ages of deposition range from 2150 Ma (Rb-Sr, Schimann, 1978) to 1590 Ma (Rb-Sr, Brooks and Arndt, quoted in Schmidt, 1980). These ages are for volcanic rocks of the Cape Smith Belt and Belcher Basin, respectively. For each segment there is some uncertainty as to the significance of individual age deteminations, whether they represent metamorphism or deposition, however, the range in ages noted above suggests that the Circum-Superior Belt segments, which can be broadly grouped into the Aphebian, may not have been developed contemporaneously.

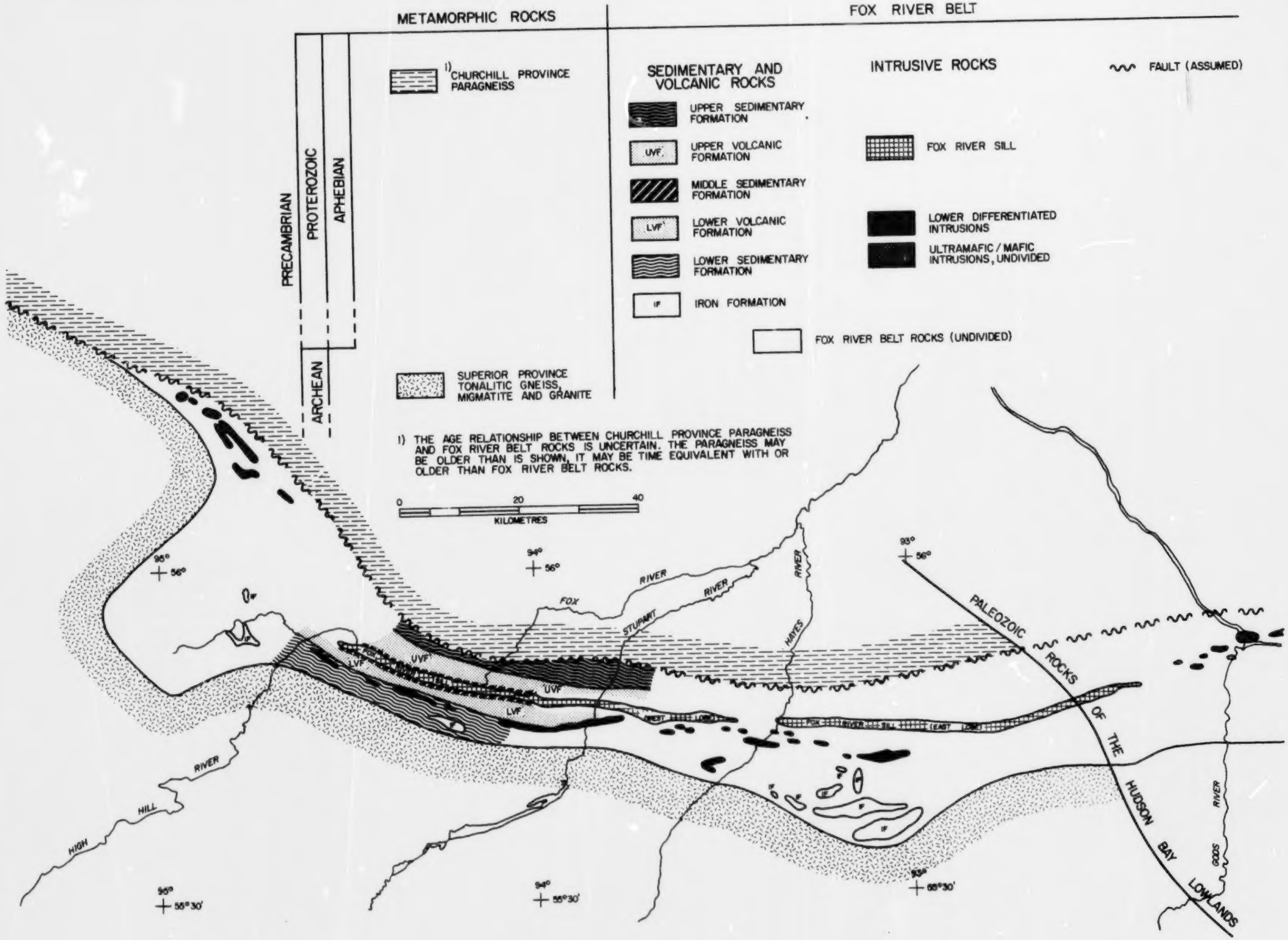
PREVIOUS WORK

Bell (1879), Brock (1911), and Merritt (1925) surveyed the general area of the Fox River, and Merritt made the first reference to ultramafic rocks on the Fox River. Springer (1941) traversed the Fox, Bigstone and Stupart Rivers, and noted volcanic and sedimentary rocks. Quinn (1955a, 1955b) made reference to a layered ultramafic

	METAMORPHIC ROCKS	FOX RIVER BELT			
		SEDIMENTARY AND VOLCANIC ROCKS		INTRUSIVE ROCKS	
PRECAMBRIAN PROTEROZOIC APHEBIAN	**¹Paragneiss of the Churchill Province (Northern Gneiss)** contact with Fox River Belt rocks exposed in DDH 38505 – faulted contact? — contact with Archean gneiss not exposed-faulted contact?		¹contact with Churchill Province paragneiss exposed in DDH 38505 — faulted contact?		
		Upper sedimentary formation	²(1.0-2.0 km) argillite, shale, carbonaceous shale		
			contact exposed in DDH 38507 — conformable?		intrusive contact
		Upper volcanic formation	²(2.5-3.4 km) massive and layered komatiitic basalt, **pillowed and massive olivine clinopyroxenite,** pillowed and massive basalt	Fox River Sill	²(2.0 km) **differentiated, stratiform, ultramafic-mafic intrusion** (intrusive into Middle sedimentary formation rocks and interpreted to be time equivalent with the extrusion of Upper volcanic formation lavas)
			contact exposed in DDH 38579 and 11921 — conformable?		intrusive contact
		Middle sedimentary formation	²(0.3-0.8 km) quartz-bearing siltstone, sandstone and argillite (host to Fox River Sill)		
			contact not exposed — conformable?		intrusive contact
		Lower volcanic formation	²(2.0-2.5 km) massive and layered komatiitic basalt, **pillowed and massive olivine clinopyroxenite,** pillowed and massive basalt	Lower differentiated intrusions	²(0.8 km) **differentiated ultramafic-mafic intrusions** (intrusive into Lower sedimentary formation rocks and interpreted to be time equivalent with the extrusion of Lower volcanic lavas)
			contact exposed in DDH 13214 — conformable?		intrusive contact
		Lower sedimentary formation	³(4.0-4.5 km) argillite, siltstone, shale, sandstone, dolomite and iron formation (host to Lower differentiated instructions)		
			contact with Superior Province Archean gneiss not exposed — faulted contact?		
	contacts between Archean gneiss and Churchill Province paragneiss and Fox River Belt rocks not exposed – faulted contacts?				
ARCHEAN	Archean gneiss of the Superior Province craton (Southern Gneiss)				

1) The age relation between Churchill Province paragneiss and Fox River Belt rocks is uncertain. The paragneiss may be older than is shown. It may be time equivalent with, or older than Fox River Belt rocks
2) Thickness estimate
3) True thickness probably less than this as there is evidence of folding toward the base of the formation

TABLE 1: Table of Formations


METAMORPHIC ROCKS
FOX RIVER BELT
PRECAMBRIAN
PROTEROZOIC
APHEBIAN
ARCHEAN
1) CHURCHILL PROVINCE PARAGNEISS
SUPERIOR PROVINCE TONALITIC GNEISS, MIGMATITE AND GRANITE
SEDIMENTARY AND VOLCANIC ROCKS
UPPER SEDIMENTARY FORMATION
UVF UPPER VOLCANIC FORMATION
MIDDLE SEDIMENTARY FORMATION
LVF LOWER VOLCANIC FORMATION
LOWER SEDIMENTARY FORMATION
IF IRON FORMATION
FOX RIVER BELT ROCKS (UNDIVIDED)
INTRUSIVE ROCKS
FOX RIVER SILL
LOWER DIFFERENTIATED INTRUSIONS
ULTRAMAFIC / MAFIC INTRUSIONS, UNDIVIDED
FAULT (ASSUMED)
0
20
40
KILOMETRES
95° 56°
94° 56°
93° 56°
95° 55°30'
94° 55°30'
93° 55°30'
FOX RIVER
STUPART RIVER
HAYES RIVER
HIGH HILL RIVER
GODS RIVER
PALEOZOIC ROCKS OF THE HUDSON BAY LOWLANDS
UVF
LVF
WEST LOBE
FOX RIVER SILL EAST LOBE
IF

1) THE AGE RELATIONSHIP BETWEEN CHURCHILL PROVINCE PARAGNEISS AND FOX RIVER BELT ROCKS IS UNCERTAIN. THE PARAGNEISS MAY BE OLDER THAN IS SHOWN, IT MAY BE TIME EQUIVALENT WITH OR OLDER THAN FOX RIVER BELT ROCKS.

FIGURE 2: General geology of the Fox River Belt

sill exposed in rapids of the Fox River. He did not distinguish between Fox River volcanic rocks, and volcanic rocks exposed on High Hill, Utik and Knee Lakes, all of which he termed Hayes River Group after Wright (1932). In a similar fashion, Potter (1962) tentatively correlated volcanic rocks of the Fox River Belt, and a belt of volcanic rocks exposed on the Semmens and Gods Rivers with Hayes River Group volcanic rocks. He also suggested that the ultramafic rocks exposed on the Stupart River were the eastern extension of the ultramafic sill described by Quinn (op. cit.) on the Fox River.

The Fox River Belt has been suggested as being the link necessary to correlate rocks of the Thompson Nickel Belt in central Manitoba with rocks of the Circum-Ungava geosyncline. Bell (1971) proposed that the ultramafic rocks of the Fox River Belt occupied a tectonic position similar to the ultramafic rocks of the Thompson Nickel Belt. He further speculated that the entire Fox River "complex" may correlate with rocks of the Circum-Ungava geosyncline. This followed a suggestion by Dimroth *et al.* (1970), that rocks of the Circum-Ungava geosyncline extend through the Belcher Islands, to the Sutton Lake area of northern Ontario, and west to the Churchill-Superior boundary zone of Manitoba. Gibb and Walcott (1971) also postulated a correlation between the Thompson, Fox River and Circum-Ungava belts on the basis of gravity anomalies. Thomas and Gibb (1977) introduced the term *Circum Superior suture* to apply to the boundary between the Churchill and Superior Provinces. Baragar and Scoates (in press) introduced the term *Circum-Superior Belt* to refer to the discontinuous segments of Aphebian supracrustal rocks that ring the Archean Superior Province craton. The Fox River Belt is one of those segments.

ACKNOWLEDGEMENTS

Field work was carried out in the Fox River area by R.F.J. Scoates in 1969, 1975, 1976 and 1977. D.L. Trueman rendered capable assistance in 1969 under arduous conditions, and M.T. Corkery, J.J. Macek, and W. Weber assisted with helicopter operations in 1975. J.J. Macek assisted with helicopter work in 1976 and W.D. McRitchie and W. Weber rendered assistance in 1977. All of these geologists have contributed enormously, not only in the collection of field data, but also in helpful and critical discussion of aspects of the local and regional geology.

This project has benefited immeasurably by the contribution of drill core from the Fox River area by International Nickel Company of Canada Limited. Access to this core (101 drill holes representing approximately 30 000 m of core) has added a critical dimension to this investigation, particularly with outcrop being scarce in the area. The generous cooperation of Inco officers and staff is acknowledged with sincere appreciation.

The drill core was logged and sampled by R.F.J. Scoates, J.J. Macek, and D.L. Trueman in the summers of 1972 and 1973. S.J.D. Parker and W. MacKenzie provided excellent assistance in 1972 and 1973, respectively, R.F.J. Scoates and M.T. Corkery completed the logging and sampling of drill core in 1974.

M.T. Corkery provided structural logs for the drill holes through careful re-examination of the core, and J.J. Macek and P. Lenton provided mineral identifications and compositional determinations. J. Timchak assisted with the mineralogical work in 1976, and D. Barchyn assisted with aeromagnetic interpretations in 1975.

Colleagues of the Geological Services Branch are acknowledged for their support and critical council, particularly J.J. Macek and M.T. Corkery, who were directly involved in field work and other aspects of the project, and A.H. Bailes, W.D. McRitchie and W. Weber who provided much insight by way of discussion into critical problems of the local and regional geology. O.R. Eckstrand, D.C. Findlay and J.M. Franklin of the Geological Survey of Canada are thanked for their continued interest in the project.

Portions of a previous version of the manuscript were examined by J.J. Macek and W. Weber. W.D. McRitchie critically read an earlier draft of this report. Diagrams were prepared by staff of the Draughting Section, and K. Chase and J. Malyon prepared the photomicrographs. Mrs. L. Chudy and Mrs. D. Navitka typed earlier versions of this report and Mrs. B. Thakrar typed the final version. I acknowledge the generous assistance of all of these people.

LOWER VOLCANIC FORMATION

GENERAL STATEMENT

Rocks of the Lower volcanic formation have been examined in four outcrop areas and seven diamond drill holes (Fig. 3). Portions of the upper three-quarters of the formation are exposed in outcrops along the Fox, Gowan and Stupart Rivers. Two drill holes intersected rocks of the upper part of the formation. The lower quarter of the formation is not exposed in outcrop, and has been penetrated by five drill holes (Fig. 3). The outcrop areas and drill holes provide data from the formation over a strike length of approximately 50 km. The total strike length of the formation is unknown; however, the Fox River Belt can be traced over a distance of approximately 300 km.

Primary volcanic structures are well preserved in outcrop and top directions can be determined readily. Flow tops regularly face north, and south-facing volcanic structures have not been observed. Direct interpretation of top direction from volcanic structures observed in drill core is difficult to impossible; however, the distribution of units in layered flows observed in drill core indicate north-facing sequences. The flows strike westerly to northwesterly, and dip steeply to the north. The absence of reversals in top directions, and the general consistency of flow attitudes indicates that the rocks of the formation have not suffered appreciable folding, apart from a rotation of approximately 90° about a westerly to northwesterly axis. The lack of deformation is also demonstrated by an absence of penetrative fabric in the rocks.

The change in the nature of the volcanic rocks from the base to the top of the formation is shown in a composite stratigraphic section (Fig. 4). The formation, estimated to average slightly in excess of 2 km in thickness, consists of three zones, a lower massive zone (700 m+), middle pillowed zone (1 100 m+) and an upper massive zone (400 m +).

The lower massive zone, exposed only in drill holes, comprises mafic and ultramafic sequences that are interpreted as being extrusive. Basalt, quartz-bearing basalt and clinopyroxenite are observed. In addition, layered differentiated sequences are interpreted to represent layered flows similar to those described by Arndt (1977) in Munro Township, Ontario. Pyroxene spinifex flows are also observed. The middle pillowed zone consists of pillowed olivine clinopyroxenite and basalt and some intercalated massive and layered flows. The upper massive zone consists of massive plagioclase-phyric basalt and porphyritic basalt with intercalated pillowed flows.

Laminated, sulphide-bearing, carbonaceous shales are interlayered with the volcanic rocks. These sedimentary rocks are seen only in drill core where they separate successive massive flows. The ratio of graphite to sulphide in these rocks is highly variable.

Chlorite, epidote, tremolite and sphene are the common secondary assemblage minerals of the Lower volcanic formation. Carbonate, quartz and albite are less common. Prehnite and pumpellyite are sporadically distributed throughout the middle and upper part of the formation. The irregular distribution of prehnite and pumpellyite indicates that these rocks have been recrystallized under conditions ranging from prehnite-pumpellyite facies of very low grade metamorphism, to lowermost greenschist facies. The rocks of the lower part of the formation are above the stability limit of prehnite and pumpellyite, and are lowermost greenschist facies. This suggests that the metamorphic grade decreases with stratigraphic height. Clinopyroxene is commonly preserved in the upper part of the formation, and it becomes more extensively altered to tremolite toward the base of the sequence. Primary basic plagioclase is rarely observed. Primary textures are preserved, for the most part, due to pseudomorphous replacement of the primary assemblage by secondary minerals. Rocks of the upper massive zone display increasing recrystallization upwards in the sequence, due to contact metamorphism by the overlying Fox River Sill.

The rocks of the Lower volcanic formation display a change from massive basalt, komatiitic basalt and layered flows at the base, through pillowed clinopyroxenite and basalt, to massive plagioclase-phyric basalt and porphyritic basalt at the top. Rocks characterized by pyroxene spinifex texture are common in the lower massive zone. Complex, graphic-like intergrowths between clinopyroxene and plagioclase are also a common feature of the rocks of the lower two zones.

The thickness of individual massive flows ranges from less than 1 m to approximately 90 m. It is not possible to put limits on the length of individual massive flows since the river exposures are small, and only a few metres of strike length of individual flows can be seen. Flows of similar composition and texture occur in the same stratigraphic position over distances up to 40 km; however, there is no reason to suspect that individual flows achieve this kind of length. Arndt *et al.* (1977) in their study of flows in Munro Township, Ontario, stated that peridotitic komatiite flows range in length from 5 m to at least 200 m, pyroxenitic komatiite flows range up to hundreds of metres in good outcrop, and basaltic komatiite flows can be traced for 2 km. Similar limitations apply to determining the dimensions of individual pillowed flows which range down to less than 1 m thick (one pillow thick) between successive massive flow units. The upper thickness limit of pillowed flow units is unknown.

The Lower volcanic formation is better exposed in outcrops and drill core, of the two volcanic formations. As it is not completely exposed from base to top in any one area, the stratigraphy is based on data from different areas, extrapolated onto a common plane. The continuity of stratigraphy with strike is based on the presence of Upper massive zone rocks along approximately 40 km and the extent of the lower differentiated intrusions over 50 km. The continuity of the west lobe of the Fox River Sill along 70 km of strike length gives added emphasis to the continuity of the stratigraphy. The lower massive zone, on the other hand, is known only in the western part of the map area, and it apparently becomes thinner eastward, and may pinch out altogether near the Stupart River. The composite stratigraphic section for the Lower volcanic formation includes the average thickness for the lower massive zone in the western part of the map area (Fig. 4).

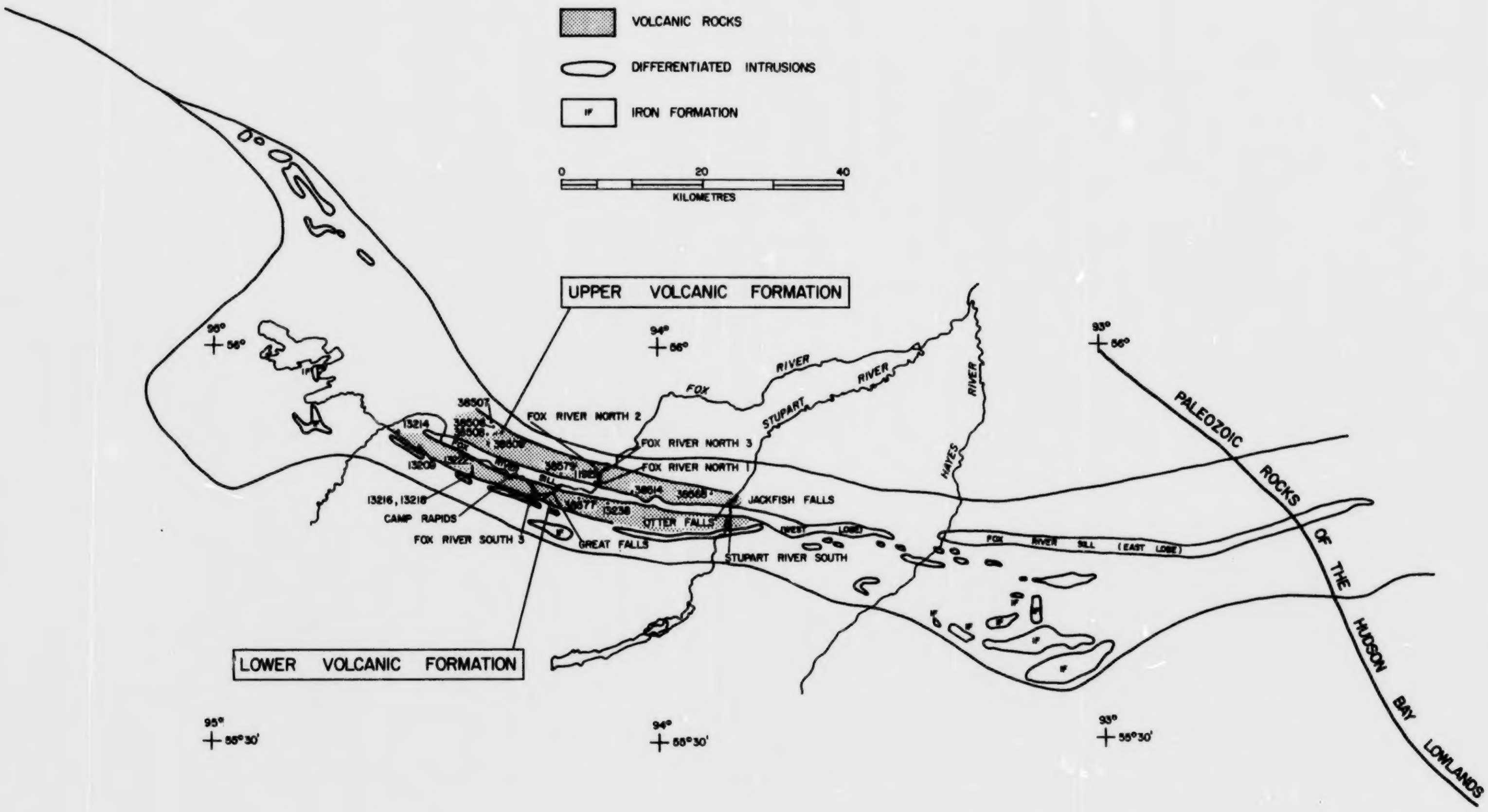
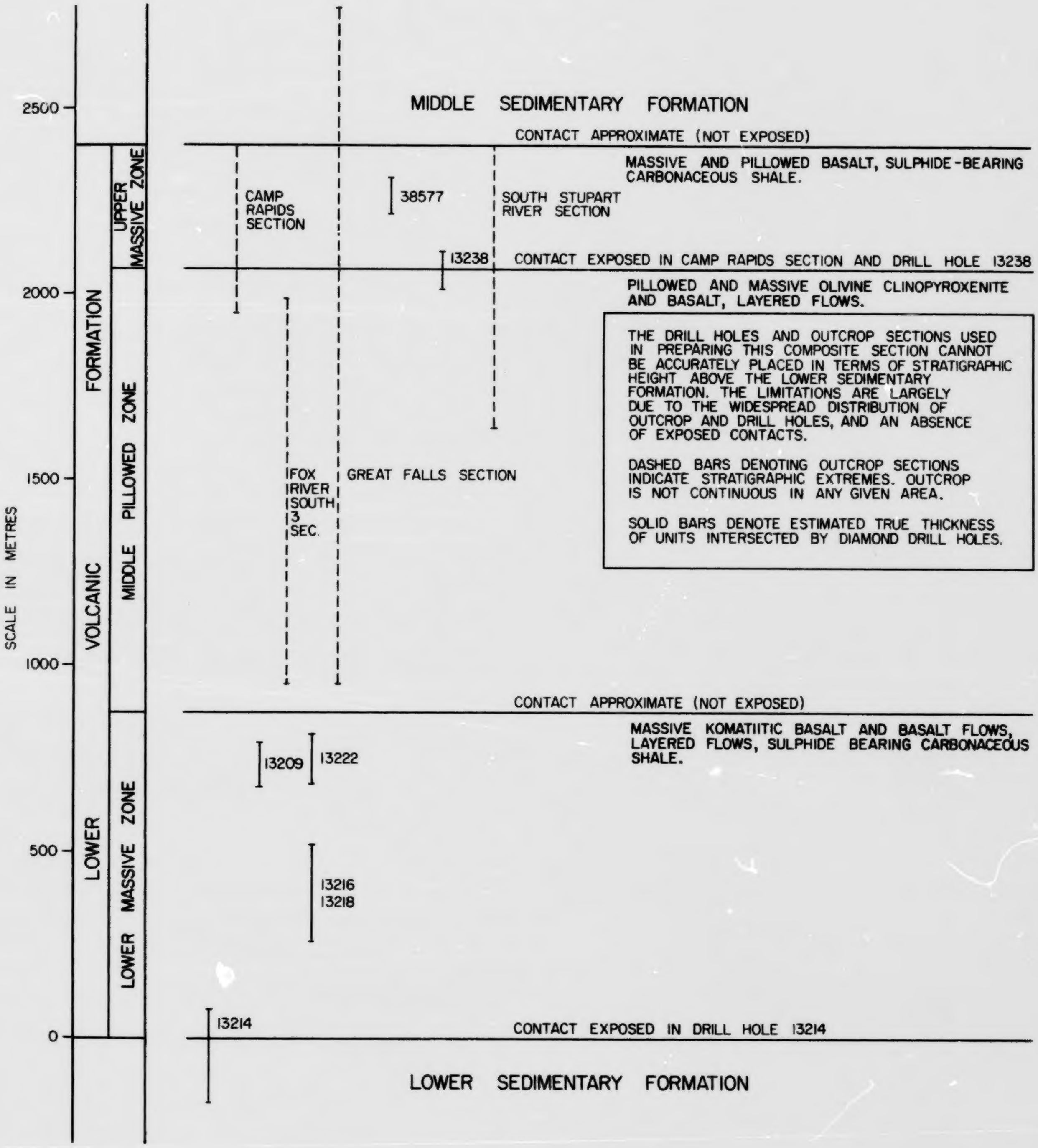

VOLCANIC ROCKS
DIFFERENTIATED INTRUSIONS
IF
IRON FORMATION
0
20
40
KILOMETRES
UPPER VOLCANIC FORMATION
LOWER VOLCANIC FORMATION
95°
56°
94°
56°
93°
56°
95°
55°30'
94°
55°30'
93°
55°30'
FOX
RIVER
STUPART
RIVER
HAYES
RIVER
36507
36506
36508
36509
13214
13209
13216, 13218
36579
36514
36568
36577
13238
CAMP RAPIDS
FOX RIVER SOUTH 3
FOX RIVER NORTH 2
FOX RIVER NORTH 3
FOX RIVER NORTH 1
JACKFISH FALLS
OTTER FALLS
GREAT FALLS
STUPART RIVER SOUTH
WEST LOBE
FOX RIVER SILL (EAST LOBE)
PALEOZOIC ROCKS OF THE HUDSON BAY LOWLANDS

FIGURE 3: Location of outcrop sections and drill holes used in examining Fox River volcanic rocks


SCALE IN METRES
2500
2000
1500
1000
500
0
LOWER VOLCANIC FORMATION
UPPER MASSIVE ZONE
MIDDLE PILLOWED ZONE
LOWER MASSIVE ZONE
MIDDLE SEDIMENTARY FORMATION
CONTACT APPROXIMATE (NOT EXPOSED)
MASSIVE AND PILLOWED BASALT, SULPHIDE-BEARING CARBONACEOUS SHALE.
CAMP RAPIDS SECTION
38577
SOUTH STUPART RIVER SECTION
13238
CONTACT EXPOSED IN CAMP RAPIDS SECTION AND DRILL HOLE 13238
PILLOWED AND MASSIVE OLIVINE CLINOPYROXENITE AND BASALT, LAYERED FLOWS.
FOX RIVER SOUTH 3 SEC.
GREAT FALLS SECTION
CONTACT APPROXIMATE (NOT EXPOSED)
MASSIVE KOMATIITIC BASALT AND BASALT FLOWS, LAYERED FLOWS, SULPHIDE BEARING CARBONACEOUS SHALE.
13209
13222
13216
13218
13214
CONTACT EXPOSED IN DRILL HOLE 13214
LOWER SEDIMENTARY FORMATION

THE DRILL HOLES AND OUTCROP SECTIONS USED IN PREPARING THIS COMPOSITE SECTION CANNOT BE ACCURATELY PLACED IN TERMS OF STRATIGRAPHIC HEIGHT ABOVE THE LOWER SEDIMENTARY FORMATION. THE LIMITATIONS ARE LARGELY DUE TO THE WIDESPREAD DISTRIBUTION OF OUTCROP AND DRILL HOLES, AND AN ABSENCE OF EXPOSED CONTACTS.

DASHED BARS DENOTING OUTCROP SECTIONS INDICATE STRATIGRAPHIC EXTREMES. OUTCROP IS NOT CONTINUOUS IN ANY GIVEN AREA.

SOLID BARS DENOTE ESTIMATED TRUE THICKNESS OF UNITS INTERSECTED BY DIAMOND DRILL HOLES.

FIGURE 4: Composite section, Lower volcanic formation

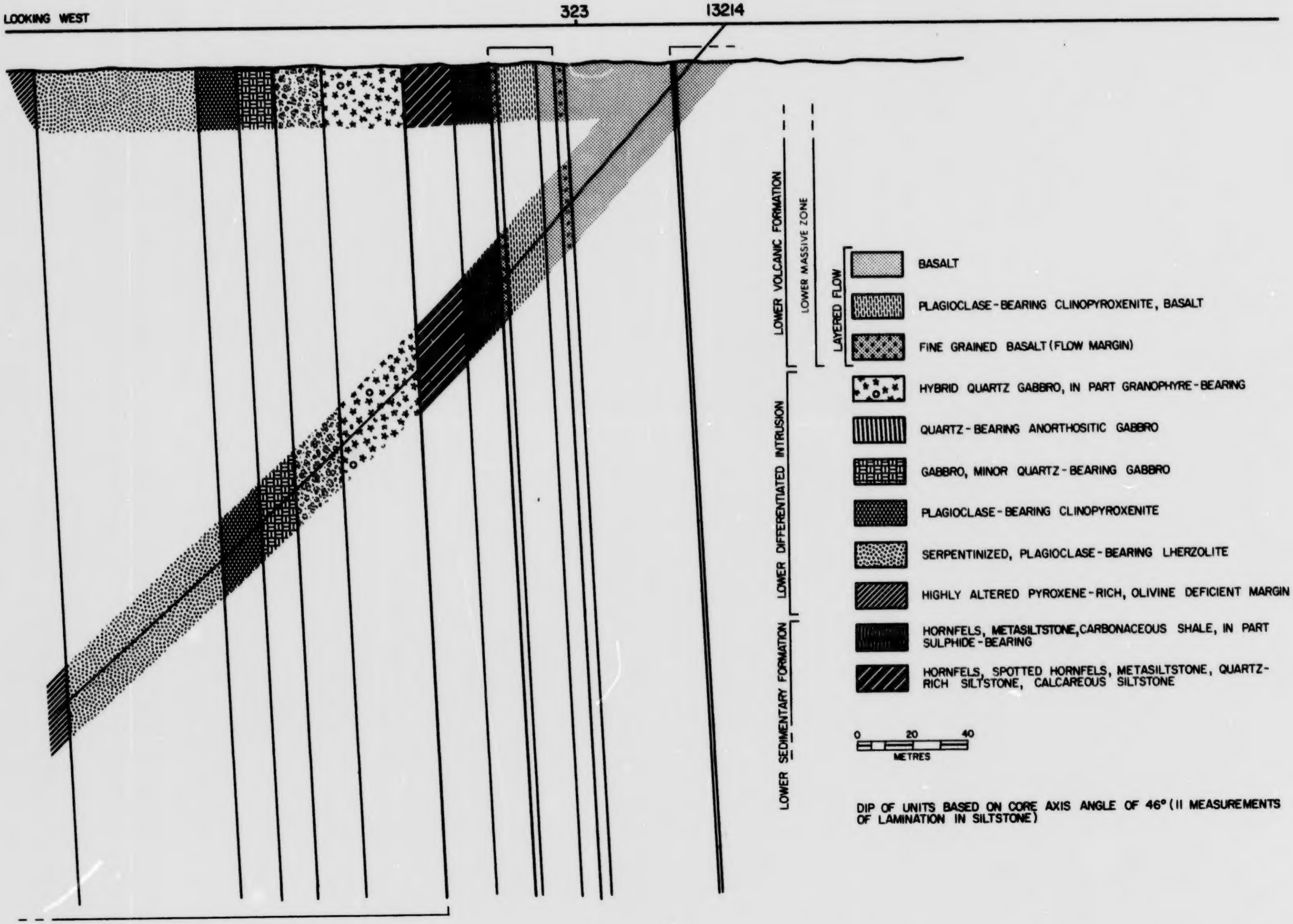

LOOKING WEST
323
13214
LOWER VOLCANIC FORMATION
LOWER MASSIVE ZONE
LAYERED FLOW
LOWER DIFFERENTIATED INTRUSION
LOWER SEDIMENTARY FORMATION
BASALT
PLAGIOCLASE-BEARING CLINOPYROXENITE, BASALT
FINE GRAINED BASALT (FLOW MARGIN)
HYBRID QUARTZ GABBRO, IN PART GRANOPHYRE-BEARING
QUARTZ-BEARING ANORTHOSITIC GABBRO
GABBRO, MINOR QUARTZ-BEARING GABBRO
PLAGIOCLASE-BEARING CLINOPYROXENITE
SERPENTINIZED, PLAGIOCLASE-BEARING LHERZOLITE
HIGHLY ALTERED PYROXENE-RICH, OLIVINE DEFICIENT MARGIN
HORNFELS, METASILTSTONE, CARBONACEOUS SHALE, IN PART SULPHIDE-BEARING
HORNFELS, SPOTTED HORNFELS, METASILTSTONE, QUARTZ-RICH SILTSTONE, CALCAREOUS SILTSTONE
0
20
40
METRES
DIP OF UNITS BASED ON CORE AXIS ANGLE OF 46° (11 MEASUREMENTS OF LAMINATION IN SILTSTONE)

FIGURE 5: DDH 13214

LOWER MASSIVE ZONE

Five drill holes intersect rocks of the Lower massive zone which are not exposed in outcrop. The zone is estimated to be 700 m+ thick. Pyroxene spinifex, complex, graphic-like clinopyroxene-plagioclase intergrowths, and fine grained, vesiculated rocks attest the extrusive nature of this suite. Other features which may be indicative of extrusive origin include the preservation of hour-glass zoning in highly recrystallized cumulus clinopyroxenes, and irregular patches of fine grained, nearly isotropic chlorite which are interpreted as altered glass. North-facing top directions are defined from the distribution of units in layered flow sequences.

Approximately 75 m of mafic rocks, representing the lowermost part of the Lower volcanic formation, are intersected by drill hole 13214 (Fig. 5). This sequence overlies 30 m of hornfelsed siltstone and carbonaceous shale that is interpreted as representing the uppermost part of the Lower sedimentary formation. The lowermost flows of the Lower volcanic formation comprise a 24 m thick, layered clinopyroxenite-basalt flow, overlain by a 40 m thick basalt flow. Flow units are defined by narrow (2 m±), fine grained assemblages which are considered to represent flow margins. The basaltic flow is characterized by altered poikilitic clinopyroxene grains (3 x 2 mm), and completely altered plagioclase laths and prisms (0.3 x 0.2 mm). A fine grained marginal unit separates this flow from the next overlying flow, of which only the lowermost 7 m is intersected by the drill hole (Fig. 5).

LAYERED FLOWS

Rocks similar to those intersected in drill hole 13214 are also observed in drill holes 13209 (Fig. 6), 13216, 13218, and 13222. In addition, layered, differentiated sequences ranging in composition from peridotite (plagioclase-bearing wehrlite) through pyroxenite to gabbro have been intersected in 13218 and 13222 (Fig. 7). These layered sequences, which are similar to the thick layered peridotite-gabbro lava flows in Munro Township, Ontario (Arndt, 1977), are considered to be layered flows. The layered flows overlie the clinopyroxenite-basalt sequence exposed in drill hole 13214, and are interlayered with basalt and komatiitic basalt flows (drill holes 13216, 13218 and 13222).

Lower volcanic formation layered flows are composed of five component parts or zones. From base to top these are: a basal contact zone, olivine cumulate zone, clinopyroxenite zone, gabbro zone and a flow top breccia (Fig. 8). The complete layered flow exposed in drill hole 13218 is approximately 90 m thick.

The rocks of basal contact zones are medium grained and tremolite-bearing, and appear to have been originally clinopyroxene-rich. Plagioclase was a primary phase, and the amount of olivine originally present is unknown, but is considered to be small. Skeletal clinopyroxene crystals have been observed in the better preserved rocks, and complex clinopyroxene-plagioclase intergrowths have been identified in one basal contact zone. The basal contact zones were originally clinopyroxenitic to gabbroic in composition.

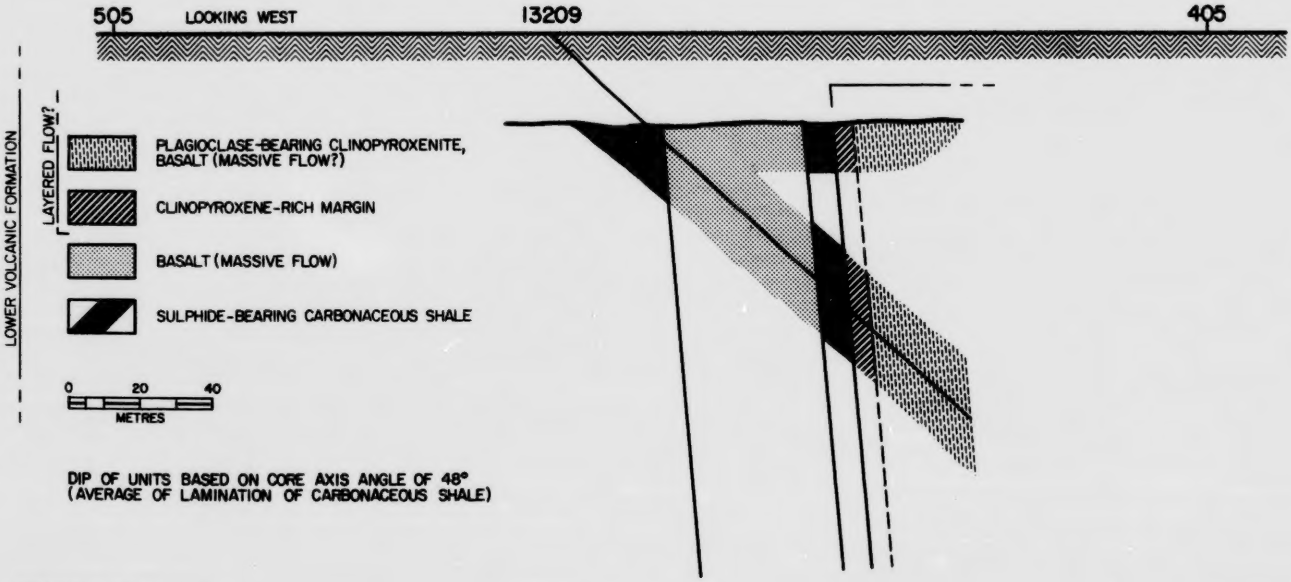

505
LOOKING WEST
13209
405
LOWER VOLCANIC FORMATION
LAYERED FLOW?
PLAGIOCLASE-BEARING CLINOPYROXENITE, BASALT (MASSIVE FLOW?)
CLINOPYROXENE-RICH MARGIN
BASALT (MASSIVE FLOW)
SULPHIDE-BEARING CARBONACEOUS SHALE
0
20
40
METRES
DIP OF UNITS BASED ON CORE AXIS ANGLE OF 48°
(AVERAGE OF LAMINATION OF CARBONACEOUS SHALE)

FIGURE 6: DDH 13209

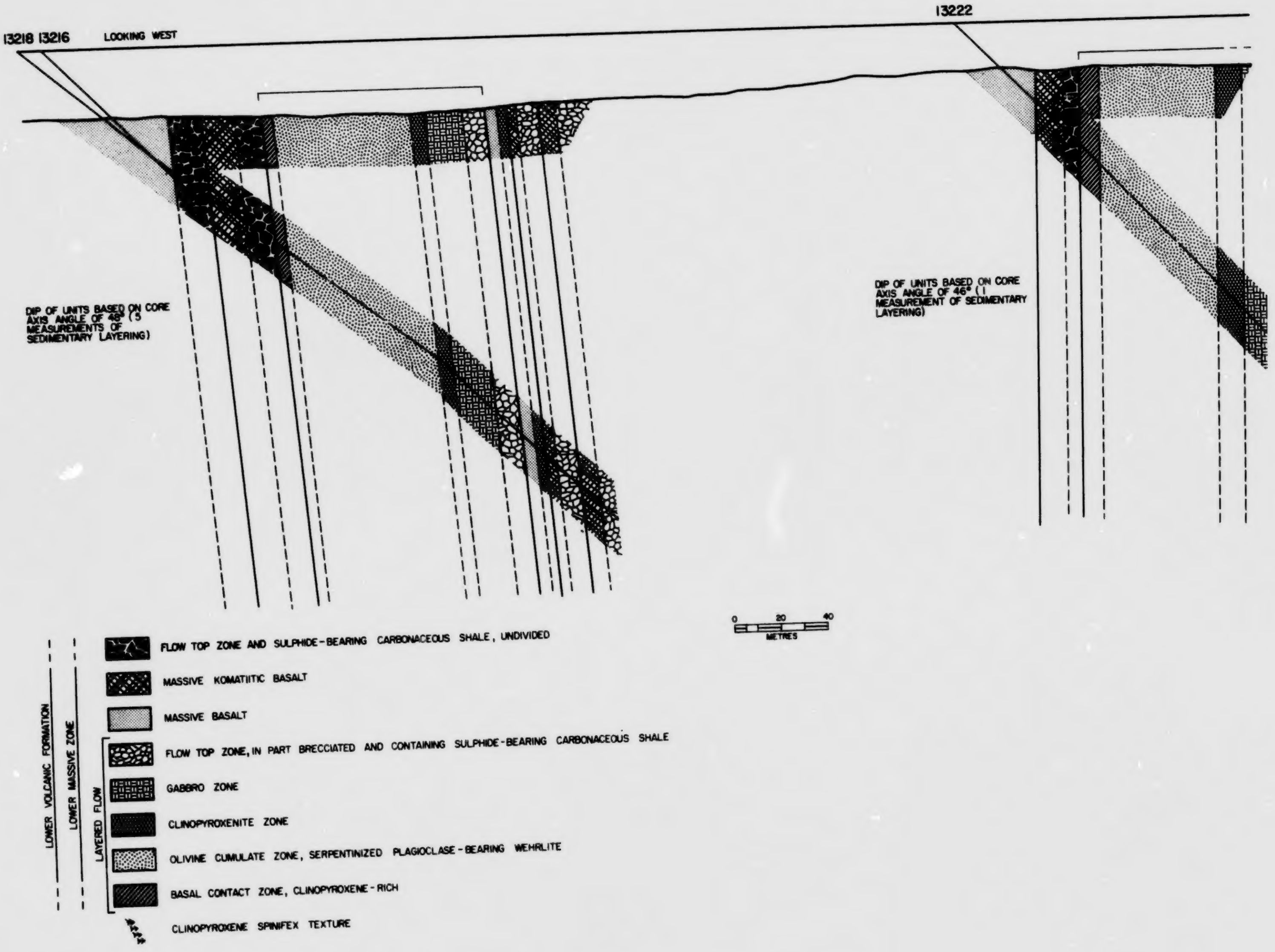

13218 13216
LOOKING WEST
13222
DIP OF UNITS BASED ON CORE AXIS ANGLE OF 48° (5 MEASUREMENTS OF SEDIMENTARY LAYERING)
DIP OF UNITS BASED ON CORE AXIS ANGLE OF 46° (1 MEASUREMENT OF SEDIMENTARY LAYERING)
0
20
40
METRES
LOWER VOLCANIC FORMATION
LOWER MASSIVE ZONE
LAYERED FLOW
FLOW TOP ZONE AND SULPHIDE-BEARING CARBONACEOUS SHALE, UNDIVIDED
MASSIVE KOMATIITIC BASALT
MASSIVE BASALT
FLOW TOP ZONE, IN PART BRECCIATED AND CONTAINING SULPHIDE-BEARING CARBONACEOUS SHALE
GABBRO ZONE
CLINOPYROXENITE ZONE
OLIVINE CUMULATE ZONE, SERPENTINIZED PLAGIOCLASE-BEARING WEHRLITE
BASAL CONTACT ZONE, CLINOPYROXENE-RICH
CLINOPYROXENE SPINIFEX TEXTURE

FIGURE 7: DDH 13216, 13218 and 13222

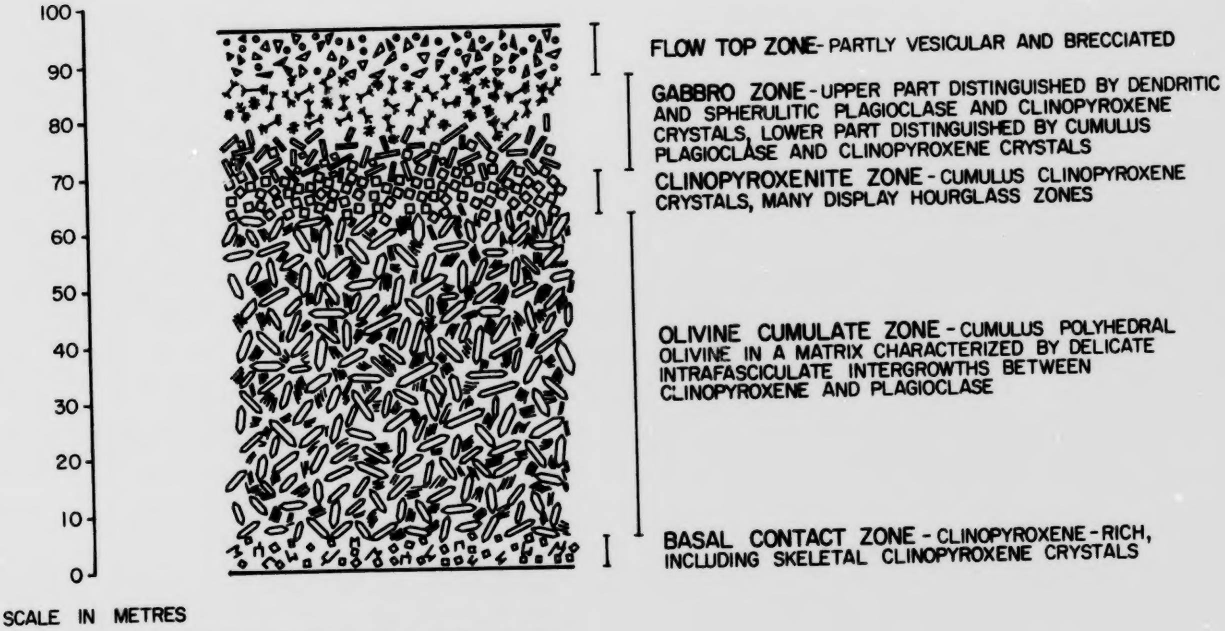

100
90
80
70
60
50
40
30
20
10
0
SCALE IN METRES
FLOW TOP ZONE- PARTLY VESICULAR AND BRECCIATED
GABBRO ZONE - UPPER PART DISTINGUISHED BY DENDRITIC AND SPHERULITIC PLAGIOCLASE AND CLINOPYROXENE CRYSTALS, LOWER PART DISTINGUISHED BY CUMULUS PLAGIOCLASE AND CLINOPYROXENE CRYSTALS
CLINOPYROXENITE ZONE - CUMULUS CLINOPYROXENE CRYSTALS, MANY DISPLAY HOURGLASS ZONES
OLIVINE CUMULATE ZONE - CUMULUS POLYHEDRAL OLIVINE IN A MATRIX CHARACTERIZED BY DELICATE INTRAFASCICULATE INTERGROWTHS BETWEEN CLINOPYROXENE AND PLAGIOCLASE
BASAL CONTACT ZONE - CLINOPYROXENE - RICH, INCLUDING SKELETAL CLINOPYROXENE CRYSTALS

FIGURE 8: Lower volcanic formation layered flow, lower zone type.

The olivine cumulate zone, dominantly plagioclase-bearing wehrlite, overlies the basal contact zone. The lowermost 20 m of this unit is strongly recrystallized, with tremolite and chlorite being the common secondary minerals. Above the strongly recrystallized area, the original texture of the rock is moderately well-preserved, due to the preservation of clinopyroxene, and the pseudomorphous replacement of plagioclase by very fine grained, nearly isotropic chlorite. The preservation of the intercumulus minerals preserves the original texture, even though olivine has been replaced by non-pseudomorphous serpentine. The rock is characterized by cumulus, polyhedral olivine crystals with slightly rounded outlines, in a groundmass of clinopyroxene and completely altered, elongate plagioclase laths. The original polyhedral olivine crystals range from 0.2 to 3.0 mm, and average 0.6 mm in their long dimension. Several examples of preferred orientation of the original olivines have been observed. Clinopyroxene occurs as irregularly shaped grains, and aggregates of irregularly shaped grains occupying the intercumulus areas. Some of the clinopyroxene crystals possess hollow cores. Alternating laths and spears of nearly isotropic chlorite and tremolite ± non-isotropic chlorite ± talc characterize much of the interstitial area between the altered olivine crystals. Some of the isotropic chlorite blades are curvilinear and occur as bundles with a subradial or fan shape. Since nearly isotropic chlorite replaces plagioclase in other serpentinized plagioclase-bearing peridotites, it is not unreasonable to conclude that here it is pseudomorphously replacing original plagioclase. The resulting texture could therefore be due to pseudomorphous preservation of an original complex intergrowth between clinopyroxene (tremolite ± chlorite ± talc) and plagioclase (isotropic chlorite). Similar, preserved, complex intergrowths between clinopyroxene and plagioclase are a distinguishing feature of the upper part of the gabbroic portion of layered flows. This textural feature, which is absent in the olivine-rich rocks of the peridotite zone of the lower differentiated intrusions, distinguishes the peridotites or olivine cumulus zones of flows from the peridotites of the differentiated intrusions. Although this textural feature could be secondary in origin and not reflect a primary texture, the fact that it is restricted to olivine-rich rocks of flows indicates that a primary origin is probable. Some areas interstitial to olivine are occupied by contiguous, nearly isotropic chlorite, that may have replaced original poikilitic plagioclase crystals. Other portions of the area interstitial to olivine, and containing fine grained clinopyroxene crystals, consists of nearly featureless serpentine, that may represent alteration of an original glass.

Olivine is totally recrystallized to very fine grained aggregates or mattes of serpentine. The serpentine has the interlocking texture characteristic of non-pseudomorphous textures (Wicks and Whittaker, 1977); however, hour-glass textures have been observed in some serpentines where partial mesh-textures are preserved. Replacement of the serpentine by fibres, and radiating bundles of fibres of fine grained colourless amphibole has been noted. The plagioclase is pseudomorphously recrystallized to a very fine grained nearly isotropic matte of chlorite.

Medium grained, cumulus, plagioclase-bearing clinopyroxenite overlies the olivine cumulate zone. The contact between the clinopyroxenite zone and the olivine cumulate zone is an area of intense alteration, however, the contact appears to be sharp. The clinopyroxene is composed of regularly shaped, equidimensional, cumulus clinopyroxene crystals, ranging from 0.2 to 1.5 mm, and averaging 0.5 mm in size, which are partially to completely replaced by tremolite. Plagioclase is totally replaced by epidote, and originally formed an interstitial phase to the cumulus clinopyroxene. Many clinopyroxene crystals display hour-glass and sector zones. Crystallization of the clinopyroxene from a liquid of gabbroic composition, is considered to have taken place subsequent to extrusion of the lava. The crystals settled to the top of the olivine cumulate zone, and crystallization of the clinopyroxene continued during and after settling of the crystals, producing well-zoned crystals. Observation of sector zoned clinopyroxene crystals is considered as additional evidence that these rocks had an extrusive origin.

Medium grained cumulus gabbro overlies, and forms a gradational contact with the clinopyroxenite. The lower part of the gabbro zone was originally composed of cumulus, zoned clinopyroxene, and plagioclase crystals. Clinopyroxene, which forms laths ranging from 0.4 x 1.0 mm to 1.0 x 0.2 mm, is poorly preserved, and extensively recrystallized to tremolite. Plagioclase, which formed laths averaging 1.0 x 0.5 mm has been extensively altered to epidote ± albite. As a result of the poor preservation of the original constituents, the primary textures are not as well preserved as in the other zones. In the upper part of the gabbro zone, plagioclase originally formed curvilinear, branching, discontinuous, dendritic grains with a skeletal appearance and many grains had a bow tie shape. Textures similar to these have been observed in plagioclase crystallized in experimental studies (Lofgren, 1974), and in plagioclase of certain lunar igneous rocks (Drever *et al.*, 1972). Terms such as sheaf spherulite, fan spherulite, bow tie, bow tie spherulite, and plumose have been used to describe these unusual plagioclase textures. The original plagioclase has been pseudomorphously replaced by albite ± epidote ± tremolite ± graphite. As a result, the primary texture is preserved despite the recrystallization of the original assemblage. The area between the branches of the altered plagioclase grains is occupied by tremolite after original clinopyroxene. Clinopyroxene appears to have occupied the central core of some plagioclase grains. In some places, the original intergrowth was almost graphic-like. The original primary texture consisted of a complex intergrowth between clinopyroxene and plagioclase, similar to that described by Drever *et al.* (1972) as being intrafasciculate. This textural relationship, although coarser grained, is similar to that previously described from the area interstitial to the olivine crystals in the olivine cumulate zone. Drever *et al.* (op. cit.) state that the pyroxene cores do not represent an intergrowth with the plagioclase, but rather represent a development within a space formed in advance of the crystallization of the core pyroxene, this space being apparently in continuity with the liquid. Ilmenite, which originally occurred as large skeletal or trellis-like crystals, is pseudomorphously replaced by sphene and other Ti-rich secondary minerals.

Highly recrystallized, very fine grained, partly brecciated rocks are interpreted as representing an original flow top breccia overlying the gabbro. Irregularly-shaped inclusions of sulphide-bearing carbonaceous shale are common, and may represent ripped-up pieces of interflow sedimentary material that became incorporated into the flow top. The flow top material was originally vesicular, and the vesicles are now filled with chlorite ± quartz ± epidote assemblages.

ORIGIN OF THE LAYERED FLOWS

The layered flows are considered to represent extrusion of olivine-charged lava (Fig. 9). The flow rate of the lava was sufficiently rapid to keep the suspended olivines away from the base of the flow where crystallization formed a clinopyroxene-rich, olivine-deficient, marginal zone. This suggests that the fluid portion of the flow was clinopyroxenitic in composition at the time of crystallization of the marginal zone. As the flow rate of the lava slowed, the suspended olivines settled to the top of the marginal zone, and formed the olivine cumulate part of the flow. The complex crystal forms displayed by some plagioclase in the interstitial areas of the rocks of the olivine cumulate zone must represent a departure from equilibrium crystal growth or non-equilibrium crystallization. Intrafasciculate textures appear to be the result of rapid crystallization (Drever *et al.*, op. cit.). Supersaturation gives rise to rapid crystallization, and a small degree of undercooling can yield a high degree of supersaturation. In this case, the interstitial fluid phase was supersaturated with plagioclase component, and gave rise to crystallization of radiating, partly hollow plagioclase laths. In a study of comb-layered rocks, Lofgren and Donaldson (1975) suggest that an abrupt change from polyhedral to skeletal or dendritic crystal morphologies indicates that conditions of supersaturation could be rapidly induced. The observation that not all of the plagioclase in the interstitial areas of the olivine cumulate zone displays complex crystal form, indicates that supersaturation in part of the zone may have been rapidly induced. Clinopyroxene subsequently crystallized, and utilized the hollow spaces within and between the already crystallized plagioclase as nucleation sites, giving rise to the complex, graphic-like intergrowths.

As crystallization proceeded, clinopyroxene became a liquidus phase, and began to accumulate on the top of the accumulated olivine of the olivine cumulate zone. Strongly sector-zoned, and hour-glass zoned crystals are characteristic of the prismatic clinopyroxene crystals of the zone, and reflect rapid crystallization. Plagioclase laths occur in the upper part of the pyroxenite zone indicating that it became a liquidus phase.

Clinopyroxene and plagioclase accumulated together to form the lower part of the gabbro zone. The upper part of the gabbro zone, which is characterized by complex, graphic-like intergrowths between clinopyroxene and plagioclase, is considered to have formed through crystallization under conditions of supersaturation in the same manner as that previously described. The fine grained, vesiculated and partly brecciated rocks overlying the gabbro is flow top material that formed when the lava was extruded.

The layered flows of the Lower volcanic formation are similar to the thick, layered peridotite-gabbro flows in Munro Township, Ontario (Arndt, 1977; Arndt, *et al.*, 1977; Arndt and Fleet, 1979). The overall similarities are in the nature of the disposition of the units, and the association of the flows with pyroxene spinifex flows. Features not identified in lower zone layered flows include the lack of a spinifex zone, a lack of orthopyroxene and a lack of rhythmic layering. On the other hand, the complex, graphic-like intergrowths between clinopyroxene and plagioclase, characteristic of some Fox River layered flows, are apparently absent from the Munro Township examples. Proterozoic layered flows have recently been described from the Cape Smith belt of northern Quebec (Arndt *et al.*, 1979). They differ from their Archean counterparts by having different upper and lower flow contacts. A layer of pillows, 1-2 m thick, occurs at the base of many of the flows, and the upper part of the gabbroic layer is fine grained and columnar jointed. This latter feature is characteristic of the upper part of layered flows of the middle pillowed zone, and of layered flows of the Upper volcanic formation.

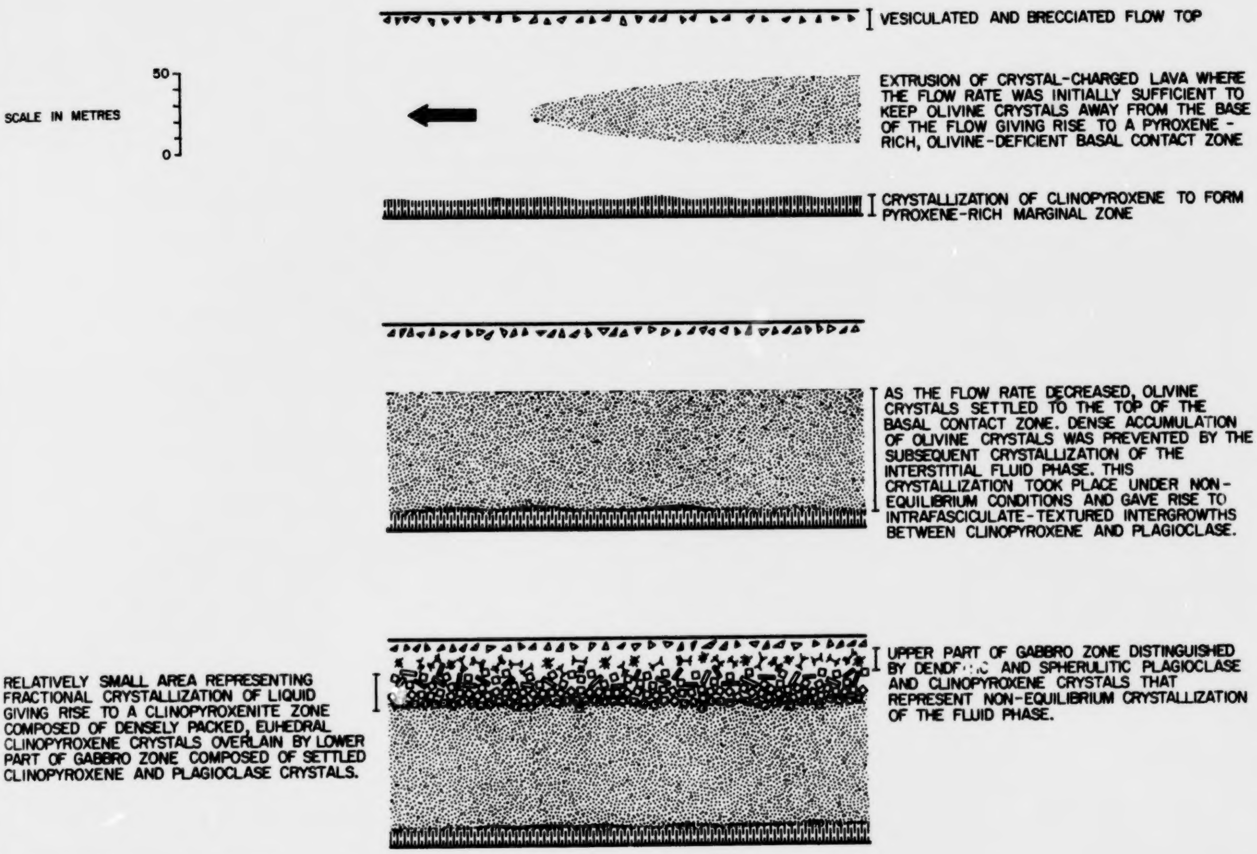
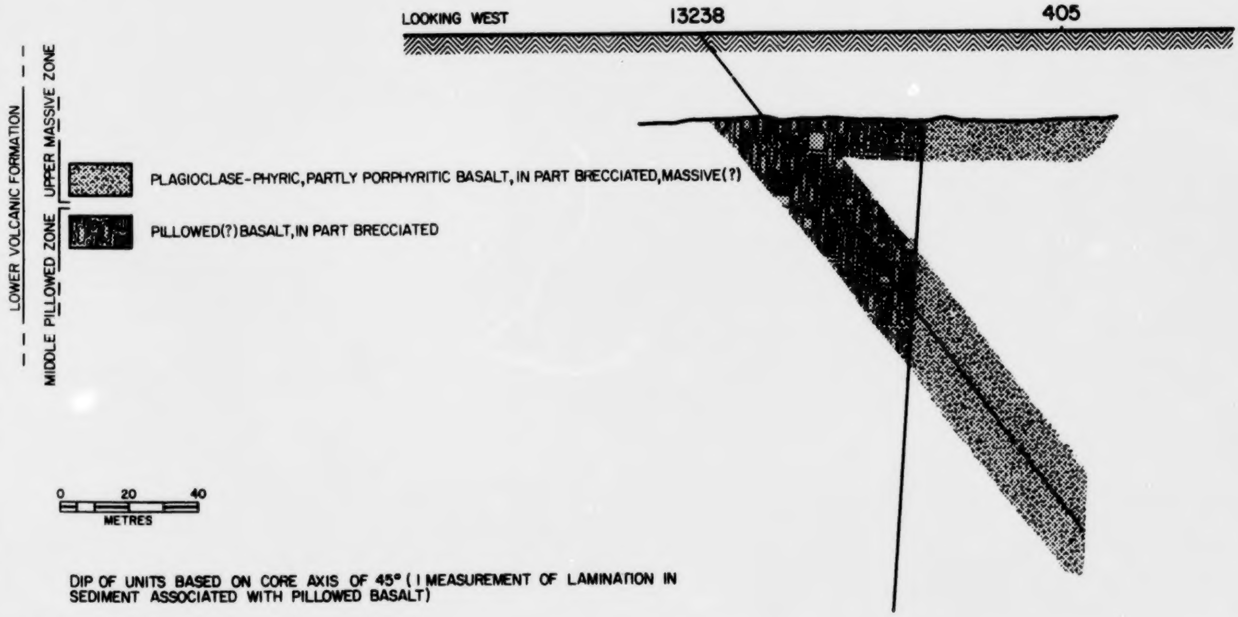

VESICULATED AND BRECCIATED FLOW TOP
50
SCALE IN METRES
0
EXTRUSION OF CRYSTAL-CHARGED LAVA WHERE THE FLOW RATE WAS INITIALLY SUFFICIENT TO KEEP OLIVINE CRYSTALS AWAY FROM THE BASE OF THE FLOW GIVING RISE TO A PYROXENE-RICH, OLIVINE-DEFICIENT BASAL CONTACT ZONE
CRYSTALLIZATION OF CLINOPYROXENE TO FORM PYROXENE-RICH MARGINAL ZONE
AS THE FLOW RATE DECREASED, OLIVINE CRYSTALS SETTLED TO THE TOP OF THE BASAL CONTACT ZONE. DENSE ACCUMULATION OF OLIVINE CRYSTALS WAS PREVENTED BY THE SUBSEQUENT CRYSTALLIZATION OF THE INTERSTITIAL FLUID PHASE. THIS CRYSTALLIZATION TOOK PLACE UNDER NON-EQUILIBRIUM CONDITIONS AND GAVE RISE TO INTRAFASCICULATE-TEXTURED INTERGROWTHS BETWEEN CLINOPYROXENE AND PLAGIOCLASE.
UPPER PART OF GABBRO ZONE DISTINGUISHED BY DENDRITIC AND SPHERULITIC PLAGIOCLASE AND CLINOPYROXENE CRYSTALS THAT REPRESENT NON-EQUILIBRIUM CRYSTALLIZATION OF THE FLUID PHASE.
RELATIVELY SMALL AREA REPRESENTING FRACTIONAL CRYSTALLIZATION OF LIQUID GIVING RISE TO A CLINOPYROXENITE ZONE COMPOSED OF DENSELY PACKED, EUHEDRAL CLINOPYROXENE CRYSTALS OVERLAIN BY LOWER PART OF GABBRO ZONE COMPOSED OF SETTLED CLINOPYROXENE AND PLAGIOCLASE CRYSTALS.

FIGURE 9: Proposed origin of Lower volcanic formation, lower zone layered flows.


LOOKING WEST
13238
405
LOWER VOLCANIC FORMATION
UPPER MASSIVE ZONE
MIDDLE PILLOWED ZONE
PLAGIOCLASE-PHYRIC, PARTLY PORPHYRITIC BASALT, IN PART BRECCIATED, MASSIVE(?)
PILLOWED(?) BASALT, IN PART BRECCIATED
0
20
40
METRES

DIP OF UNITS BASED ON CORE AXIS OF 45° (1 MEASUREMENT OF LAMINATION IN SEDIMENT ASSOCIATED WITH PILLOWED BASALT)

FIGURE 10: DDH 13238

KOMATIITIC BASALT FLOWS

Komatiitic basalt flows range from 10 to 15 m thick, and are intercalated with layered flows and basalt flows. Pyroxene spinifex characterizes the upper part of the komatiitic basalt flows, and is defined by a variety of textures involving original elongate, skeletal clinopyroxene crystals. In some examples straight to gently curving laths or blades of tremolite, pseudomorphously replacing original clinopyroxene blades, display subparallel radiate, fan-like, or plumose development of over several centimetres. Individual blades measure up to 1 cm, and average 3 to 4 mm long. Many equidimensional crystals, with original hollow cores, are interpreted as representing near basal orientations of the blade-like crystals. The crystals occur in a groundmass of albite ± quartz ± epidote ± sphene ± tremolite. The groundmass is interpreted as originally being composed of fine grained laths or acicular crystals of basic plagioclase, some of which was intergrown with fine grained clinopyroxene. None of the primary minerals are preserved in these rocks and the textures are best seen in thin section, under plane polarized light. In the upper parts of some flows, the rocks are characterized by a poorly preserved texture, that is interpreted as originally representing numerous, very fine grained individuals of skeletal clinopyroxene having bat wing or M-shapes. The skeletal crystal segments form distinctly discontinuous crystals, that have curving, bent, chevron kink, spiral and spherulitic forms (Plate 1). Rocks identical to this and in a much better state of preservation occur in komatiitic basalt flows of the Upper volcanic formation. The presence of these unusual clinopyroxene crystal morphologies is also considered to distinguish komatiitic basalt flows.

The lower part of komatiitic basalt flows consists of tremolite, pseudomorphously replacing cumulus, skeletal laths and blades of clinopyroxene (up to 5 mm long), in a matrix of branching, dendritic, curvilinear plagioclase (up to 5 mm long), showing a radiate or fan-like development intergrown with tremolite after clinopyroxene. Clinopyroxene increases in abundance toward the base of the flows. All changes through the flows, from the spinifex zone at the top, to the cumulus zone at the bottom, appear to be gradational.

The pyroxene spinifex textures appear to represent incipient crystallization of clinopyroxene from numerous nucleation sites. Each nucleation site is characterized by skeletal, bat wing or M-shaped clinopyroxene individuals. Some skeletal individuals are arranged in crude, curving, en-echelon groups that outline imperfect, curving, discontinuous crystals. Many individuals form a framework for new nucleation and crystallization. The curving or bent, disconnected crystals are commonly in groups that display parallel or sub-parallel growth. These textures represent incipient nucleation of clinopyroxene from numerous nucleation sites, probably under conditions of supersaturation. The incipient nature of the crystallization has been preserved by the quenching of the fluid phase, which gave rise to a glassy groundmass, that has been subsequently modified by alteration and low grade metamorphism.

BASALT FLOWS

Basalt flows, the other extrusive component of the Lower massive zone, range from 5 to 40 m thick, and are intercalated with layered flows and komatiitic basalt flows (Figs. 5, 6 and 7). The rocks are highly recrystallized, and only clinopyroxene is partly preserved in some rocks. Tremolite, chlorite, albite, epidote, quartz and sphene are the dominant minerals. Imperfect pseudomorphous replacement of the original assemblage renders definition of the original texture difficult. The rocks are considered to have been composed originally of a hypidiomorphic assemblage of stubby clinopyroxene prisms (2.0 — 3.0 mm), and plagioclase laths (up to 2.0 mm). Small changes in grain size, and in the ratio of clinopyroxene to plagioclase have been noted within individual flows.

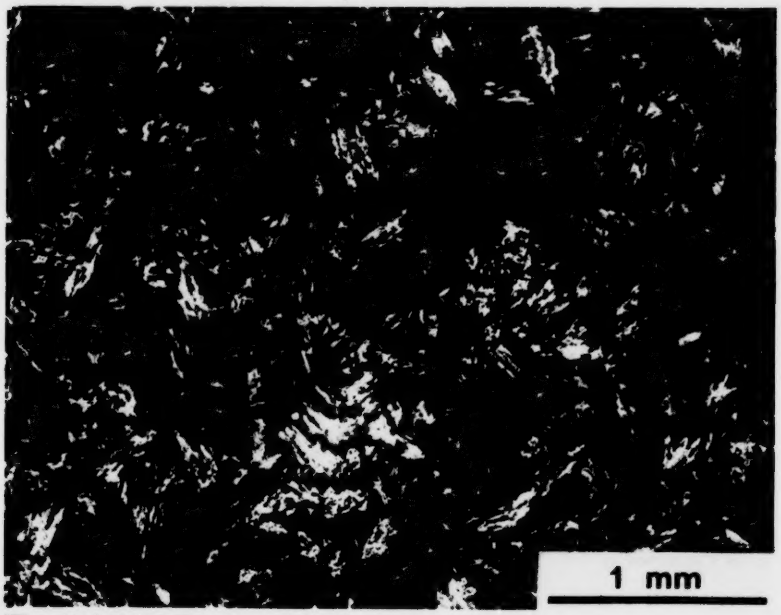


PLATE 1: Tremolite pseudomorphs after original M-, and bat wing-shaped clinopyroxene skeletal segments. Many of these individual segments were originally organized and formed disconnected, curving, bent and spiral-shaped crystals. Top of komatiitic basalt flow, Lower massive zone, Lower volcanic formation, DDH 13222 (13222-195) XN.[1]

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[1] *XN = crossed polarizers. PL = plain polarized light.*

MIDDLE PILLOWED ZONE

The middle 1200 m of the Lower volcanic formation is composed dominantly of pillowed flows, with some intercalated massive flows. The rocks are exposed in a number of outcrop areas on the Fox River, and in the Stupart River south section, and have been intersected by one diamond drill hole (Figs. 4 and 10). The rocks of the zone are mid- to dark-greyish buff on weathered surface, and mid- to dark grey-green on fresh surface. The ratio of pillowed to massive flows is estimated to be 10:1. Individual pillows range from 20 cm up to 5 x 3 m, and average 1 m x 80 cm in size. The pillows are commonly not vesiculated, although some poorly vesiculated pillows have been observed. The lack of vesicles may indicate deposition of pillows in relatively deep water. The pillows display variable shapes, ranging from the common teardrop or normal pillow shape, to highly irregular forms that drape over underlying smaller pillows (Plate 2), to elongate masses whose underside perfectly conforms with the topography of the underlying pillows. The third dimension of pillows, seen in one locality where the bedding of the flows is cut at right angles by the Fox River (Plate 3), shows that the pillows have essentially the same dimensions and shapes as on the plane or outcrop surface. The pillows in this area have the shape of flattened spheres. Near the base of the zone, the pillows tend to be tightly molded to each other with little interpillow space; however, in some areas, particularly toward the top of the zone, carbonate and quartz fill pillow interstices. The development of radially disposed joints has been noted in some pillows.

Large flat cavities have been observed in some pillows. The cavities occur from the middle to the top of the pillow as a series of flat, pancake-like openings, stacked one on top of the other (Plate 4). The openings are now filled by quartz and carbonate. The cavities represent original open spaces, perhaps gas cavities which did not coalesce prior to solidification of the lava. Hargreaves and Ayres (1979) suggested that multiple cavities represent original gas pockets, and may indicate pulsating magma supply, with each cavity representing a short hiatus in lava supply. This suggests that cavity-bearing pillows are lava tubes, through which lava was moving to new pillows at the advancing front of the flow. Cavities in pillows can be useful for indicating the original attitude of flows, since the upper surface of the liquid in incompletely filled pillows, assumes a horizontal position (Macdonald, 1972). In the pillowed zone, attitudes of the bottom surfaces of large cavities have been measured, and have been found to be identical with average attitudes of the pillowed flows in which they occur.

Variolitic pillowed flows contain pea-size (2 to 10 mm) spheres and elliptical masses, that are lighter in colour on the weathered surface than the brownish groundmass material (Plate 5). Some variolites are concentrated so that the pillow consists essentially of a dense mass of variolites. A 1 to 3 cm zone of darker coloured, groundmass material separates the variolitic core from the glassy pillow rim in such cases.

The rocks range from plagioclase-bearing olivine clinopyroxenite to basalt in mineralogical composition. The lower half of the pillowed zone is dominantly plagioclase-bearing olivine clinopyroxenite. The rocks consist of randomly oriented skeletal clinopyroxene crystals in a fine grained matrix of clinopyroxene and plagioclase (Plate 6). The skeletal clinopyroxene is strongly zoned, hour-glass and sector zones being observed. Frond-like, plumose clinopyroxene, partly replaced by tremolite is the most common groundmass constituent. Brownish, fine grained patches of amphibole are interpreted as representing altered glass. Chlorite, epidote ± carbonate pseudomorphously replaced original skeletal, hopper-shaped olivine. The original basic plagioclase has been pseudomorphously replaced by albite ± epidote. The original texture of these rocks is well-preserved, due to the preservation of clinopyroxene, and the pseudomorphous replacement of the other primary assemblage silicate minerals. Magnetite, chromite and sphene replacing ilmenite, are the accessory oxide minerals. Pyrrhotite and pyrite are rare.

The varioles, previously noted, consist of dark epidote-rich rims (0.2 mm) and central cores of tremolite, chlorite, epidote, carbonate and quartz. They appear to represent altered, originally more plagioclase-rich material compared with the pyroxene-rich groundmass.

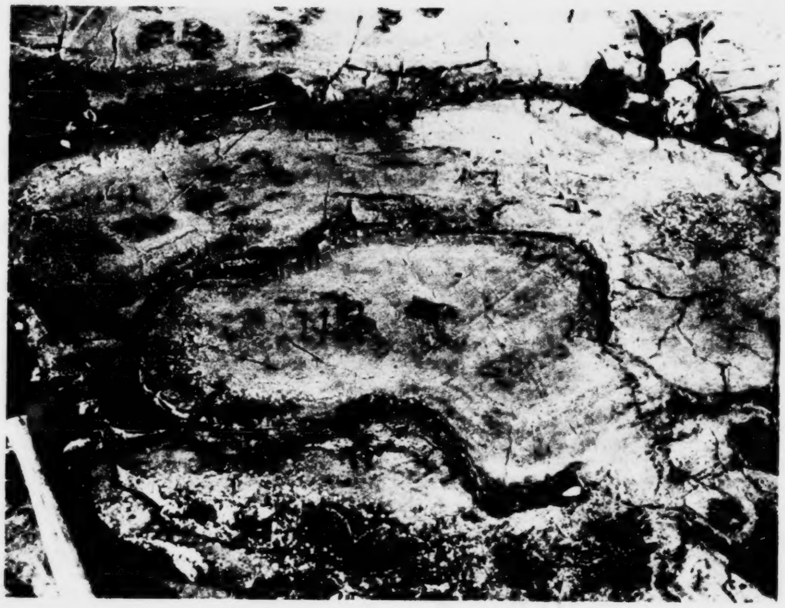
In the upper half of the pillowed zone, rocks of basaltic composition become progressively more abundant. The basalts have light buff weathered surfaces, and are greyish-green on fresh surface. The pillows tend to have elliptical shapes, and are smaller than the more mafic varieties. The pillows range from 5 x 10 cm up to 1 x 1.5 m and average 20 x 30 cm in size. The interpillow space becomes greater, and is commonly occupied by hyaloclastite breccia. The basalts are characterized by irregular, strongly zoned clinopyroxene grains, and well-formed stubby laths and prisms of plagioclase. The clinopyroxene, which has a brownish-mauve tint, suggesting that it is titaniferous augite, is slightly pleochroic, and has margins that are slightly darker in colour than the core. Many clinopyroxene grains have hour-glass and sector zones, and some larger clinopyroxene plates, poikilitically enclosing randomly oriented plagioclase laths, have been observed. Fine grained, complex intergrowths between clinopyroxene and plagioclase, in which the core of an individual plagioclase crystal is occupied by clinopyroxene, are sporadically developed. Ilmenite, now largely converted to sphene, is a common accessory mineral.

The common secondary minerals of the pillowed zone are tremolite, chlorite, epidote and sphene. Additional secondary minerals are albite, quartz and carbonate. Pumpellyite and prehnite are sporadically distributed throughout the zone. The original textures of the rocks are well-preserved because of the preservation of clinopyroxene, and the pseudomorphous replacement of the other primary assemblage minerals (Plate 7).

The pseudomorphous replacement of skeletal olivine microphenocrysts in orignally glassy rocks by chlorite ± quartz ± carbonate ± tremolite ± epidote assemblages has been observed. The grain boundaries of the original olivine with the former glassy groundmass are sharp and distinct. Many of these pseudomorphously replaced skeletal olivine crystals are selvaged by a leached haloe up to 1 mm from the crystal boundary. This suggests local geochemical readjustment during low grade metamorphism.

The secondary assemblage indicates that the rocks of the pillowed zone have been metamorphosed under conditions ranging from the prehnite-pumpellyite facies of very low grade metamorphism, to lowermost greenschist facies.

PLATE 2: Draped pillow, variolitic, plagioclase-bearing, olivine clinopyroxenite pillowed flow. Note tight molding of pillows to each other, and cavities in lowermost pillow. Tops toward top of photo. Middle pillowed zone, Lower volcanic formation, Fox River south 3 section.



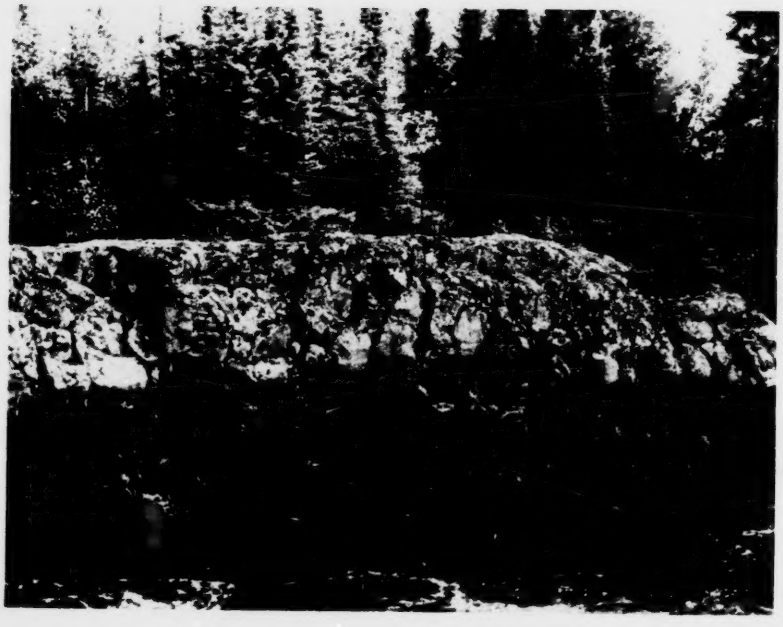
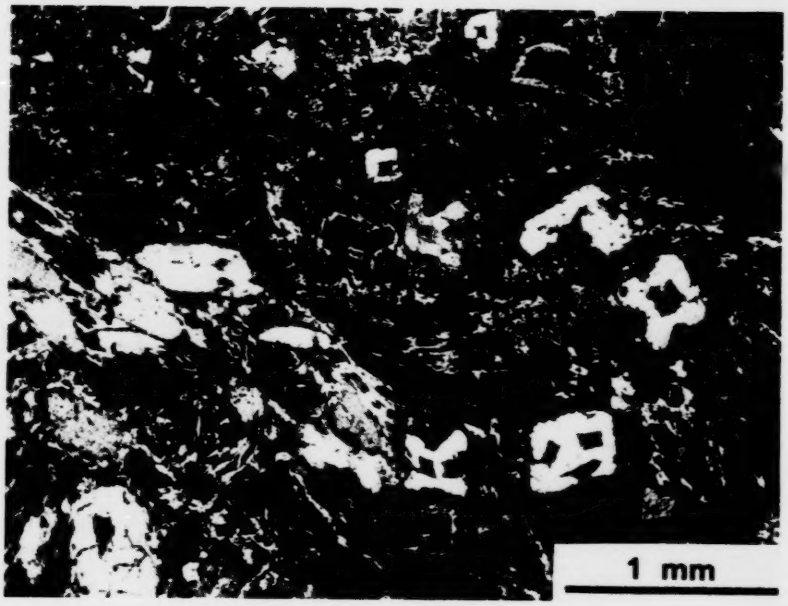


PLATE 3: Third dimensional view of olivine clinopyroxenite pillowed flow. Pillows have similar shape and size to that seen on plan view. Tops to the left. Outcrop is approximately 3 m high. Middle pillowed zone, Lower volcanic formation, Fox River south 3 section.

PLATE 4: Pillow with cavities, olivine clinopyroxenite pillowed flow. Cavities become wider toward pillow top where they split into two parts. Tops to the right. Middle pillowed zone, Lower volcanic formation, Fox River south 3 section.

PLATE 5: Variolitic pillow, plagioclase-bearing olivine clinopyroxenite pillowed flow. Note concentration of varioles in pillow centre. Tops to top of photo. Pillow is approximately 45 cm long. Middle pillowed zone, Lower volcanic formation, Fox River south 3 section.

PLATE 6: Suspended skeletal clinopyroxene segments in a groundmass composed of ragged tremolite + albite + epidote + sphene. Pillowed clinopyroxenite flow, Middle pillowed zone, Lower volcanic formation, Great Falls section, Fox River (36-75-228) XN.



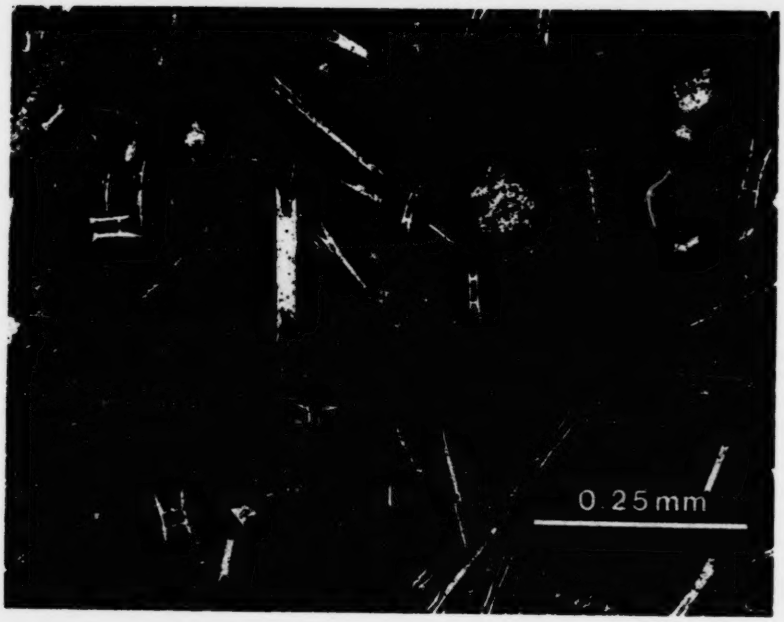


PLATE 7: Randomly disposed, skeletal plagioclase segments in an altered glass groundmass. Note swallow tail and belt buckle shapes. Pillow rim, pillowed basalt flow, Middle pillowed zone, Lower volcanic formation, Great Falls section, Fox River (03-76-97-2) PL.

MASSIVE FLOWS

Massive flows of the pillowed zone range from 1 to 2 m thick, homogeneous flows intercalated with the pillowed sequence to layered flows with a base composed of cumulus minerals overlain by a fine grained, columnar jointed upper zone.

A layered flow exposed at the west end of an elongate island in the Fox River, 1 km downstream from the confluence of the Sipanigo and Fox Rivers, is 9 m thick, and is underlain by a 2 m thick pillowed flow (Fig. 11). The pillowed flow is in turn underlain by another massive flow, of which only a portion of the upper columnar jointed zone is exposed. Overlying the layered flow is a sequence of pillowed pyroxenite and basalt. The layered flow consists of a 4 m thick, massive, lower zone that becomes extremely fine grained over the lowermost metre above the contact with the underlying flow. The massive zone is overlain by a 4 m thick, upper, fine grained zone, characterized by well-developed, curving, columnar joints. The upper columnar jointed zone grades into a 1 m thick, partly brecciated, flow top.

The medium grained, massive lower zone consists of stubby to lath-like 0.5 to 2.0 mm, strongly zoned, cumulus clinopyroxene crystals, that comprise approximately 35 percent of the rock. The crystals occur in a matrix originally composed of complex, graphic-like intergrowths between clinopyroxene and plagioclase, similar to the intergrowths found in the layered flows. The ratio of clinopyroxene to plagioclase in the matrix is estimated to have been 1:1. A minor amount of cumulus olivine was also originally present. The rock was originally a melagabbro.

The fine grained, columnar jointed upper part of the flow consists of suspended, skeletal, strongly zoned clinopyroxene crystals in a matrix originally composed of fine grained, complex intergrowths between clinopyroxene and plagioclase. Two periods of crystallization of clinopyroxene are indicated. The 0.5 to 1.0 mm skeletal, strongly zoned clinopyroxene represents an early crystallization, and the 0.5 mm brownish, matrix clinopyroxene, complexly intergrown with plagioclase, represents later matrix crystallization. The rock was originally a melagabbro.

The flow top is substantially recrystallized, and the original textures are not well preserved. The groundmass originally consisted of a fine grained matte of randomly oriented, frond-like, plumose clinopyroxene now altered to tremolite. Poorly preserved relicts of skeletal clinopyroxene are dispersed through the groundmass. Irregularly shaped, coarser grained patches render a heterogeneous nature to the rock. Vesicles are filled with assemblages of carbonate, quartz, chlorite, and epidote.

The upper, fine grained zone of the incompletely exposed lowermost massive flow, from the same outcrop area (Fig. 11), consists of elongate, curving clinopyroxene crystals which are strongly zoned, and display a sweeping extinction. The clinopyroxene crystals display brownish rims, and occur as a suspended phase in a groundmass of extremely fine grained, acicular plagioclase crystals, arranged as bundles of divergent sheaves up to 1 cm in area. Each sheaf has an orientation different from its neighbour. Vesicles filled with fine grained, nearly isotropic chlorite, some displaying an outer rim of randomly oriented epidote plates, are common. The lower part of the flow is not exposed; however, the mineralogy of the upper part of the flow indicates that it has a different composition from the more completely exposed overlying layered flow previously described.

The secondary mineral assemblage of the massive flow is similar to that of the pillowed flows. Pumpellyite and prehnite are common though not abundant, and the rocks range in metamorphic grade, from prehnite-pumpellyite facies of very low grade metamorphism, to lowermost greenschist facies.

Layered flows, similar to the flow described above, have been observed in the Upper volcanic formation on the Stupart River and Fox River, and are interpreted to occur in other areas, on the basis of diamond drill hole information.

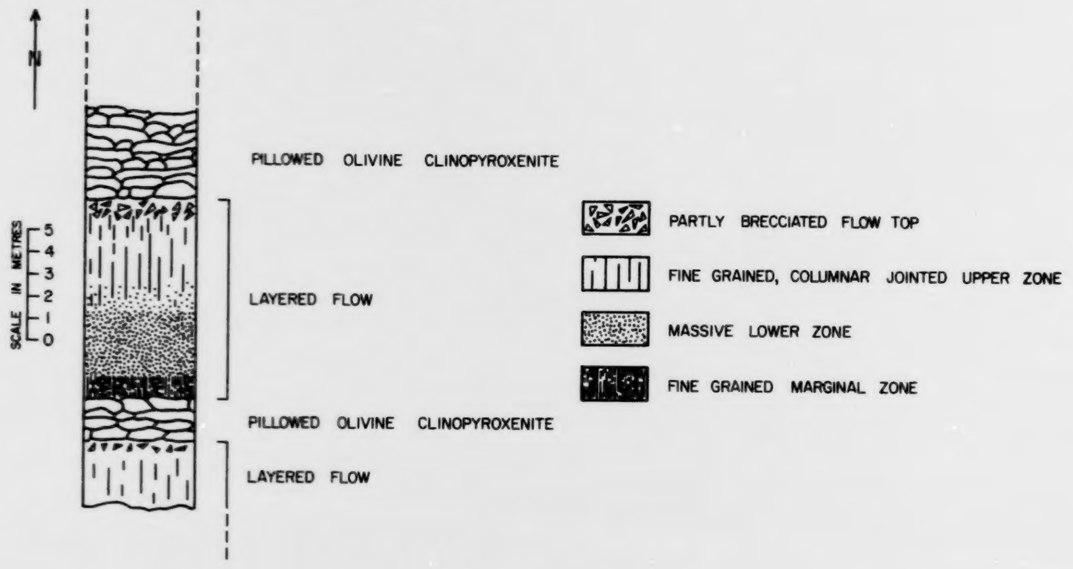

N
SCALE IN METRES
5
4
3
2
1
0
PILLOWED OLIVINE CLINOPYROXENITE
LAYERED FLOW
PILLOWED OLIVINE CLINOPYROXENITE
LAYERED FLOW
PARTLY BRECCIATED FLOW TOP
FINE GRAINED, COLUMNAR JOINTED UPPER ZONE
MASSIVE LOWER ZONE
FINE GRAINED MARGINAL ZONE

FIGURE 11: Sketch of Middle Pillowed Zone layered flow

UPPER MASSIVE ZONE

The Upper massive zone consists predominantly of massive flows. The rocks of the zone are not as well exposed as those of the middle pillowed zone, and the ratio of massive to pillowed flows is estimated to be 5:1. The contact between the middle pillowed zone, and the upper massive zone is exposed, sporadically, along the south shore of the Fox River, in the Camp Rapids outcrop area (Fig. 12). The contact is sharp, massive flows overlying pillowed flows (Plates 8 and 9). The south shore of the river is relatively straight along a distance of 800 m, and strikes 285°, which is the average strike of the flows in this area. This topographic lineament reflects the more resistant nature of the rocks of the middle pillowed zone.

PLATE 8: Contact between pillowed basalt (under hammer) of the Middle pillowed zone and massive basalt (under metal tape container) of the Upper massive zone. Uppermost pillows are outlined with white tape. Note rectangular joint pattern in massive flow. Tops to the right. Lower volcanic formation, Camp Rapids section, Fox River.

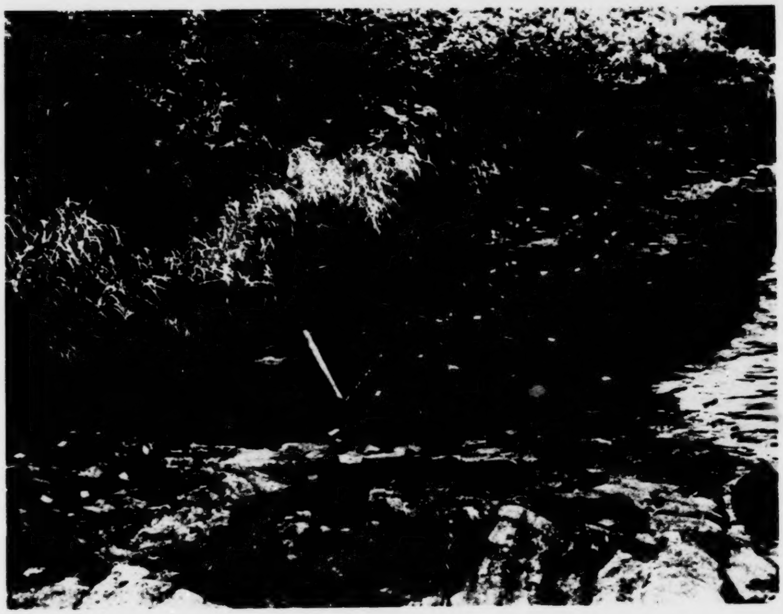


PLATE 9: Detail of contact seen in Plate 8. Large pillow is 1.5 m long. Rectangular jointing in massive flow is well-developed. Lower volcanic formation.

The rocks of the upper massive zone are predominantly light brownish-grey on weathered surface, and light greyish-green on fresh surface, and this contrasts with the much darker colours of the weathered and fresh surfaces of the rocks of the middle pillowed zone. The massive flows range down to 4 m thick, the upper limit is unknown due to poor exposure. They commonly display a fine grained, gabbroic texture, and are homogeneous across large outcrop surfaces. Flow tops are vesiculated, and some are brecciated. The 1 to 3 m thick flow top breccias consist of irregularly shaped fragments that range from a few mm up to 30 cm (Plate 10). The breccias are disorganized, and size ordering has not been observed. The fragments are homogeneous in composition, and are the same composition as the massive flows with which they are associated. Many fragments display brownish margins, presumably due to oxidation, and some are vesicular. Some breccias have an aphanitic, mid- to dark-green matrix which is interpreted as being after a glass, and this is interpreted as evidence that the massive flows were deposited subaqueously.

Individual pillows of pillowed flows, intercalated with the massive flows, are elliptical, have narrow (2 cm) selvages, and are commonly vesiculated near their margins (Plate 11). The presence of vesicles indicates deposition of the pillows in relatively shallow water, which contrasts with the relatively deep water environment suggested for the rocks of the pillowed zone. In one small outcrop area, pillows displaying delicate concentric laminations that crudely parallel the pillow margin, have been observed (Plate 11). In detail the laminations are joined by thread-like veins, that render an imperfect lace-like appearance to the rock (Plate 12). Some of these pillows have small single cavities near their centre. Similar features have been observed along strike 400 m east of the small outcrop area, and in the same relative stratigraphic position in an outcrop, on the Stupart River, 25 km to the east. The concentric laminations may be due to replacement by secondary minerals of original subconcentric cooling cracks. Concentric structures in pillows from the Dryden-Wabigoon area of northwestern Ontario are considered to be the result of filling of peripheral cracks formed as a result of cooling (Satterly, 1941). Dimroth *et al.* (1978) described subconcentric cooling cracks filled with albite in pillows from the Rouyn-Noranda area, Quebec.

A series of brecciated rocks, near the base of drill hole 38577 (Fig. 13) have textures similar to those of olivine clinopyroxenite pillowed flows. This is the only known occurrence of ultramafic lavas in upper massive zone rocks.

PLATE 10: Detail of 2 m thick flow top breccia. Disorganized aggregation of plagioclase-phyric basalt fragments, many of which display brownish rims. Lens cap is 6 cm wide. Upper massive zone, Lower volcanic formation, Great Falls section, Fox River.

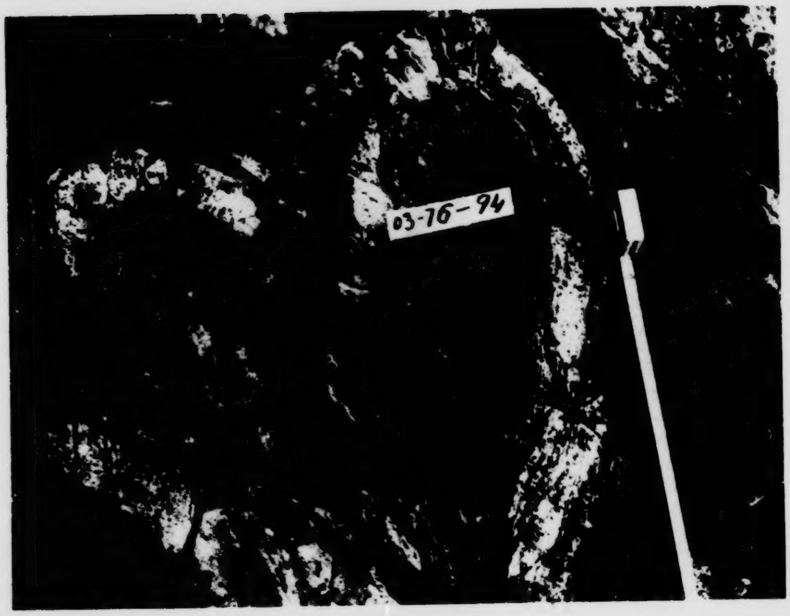


PLATE 11: Elliptical pillows, pillowed plagioclase-phyric basalt. Pillows have concentric laminations, narrow rims and are vesiculated. Tops to the left. Upper massive zone, Lower volcanic formation, Great Falls section, Fox River.

PLATE 12: Detail of concentric laminations in pillowed plagioclase-phyric basalt. The light coloured laminae are epidote-rich and are considered to be altered cooling cracks. Upper massive zone, Lower volcanic formation, Great Falls section, Fox River.

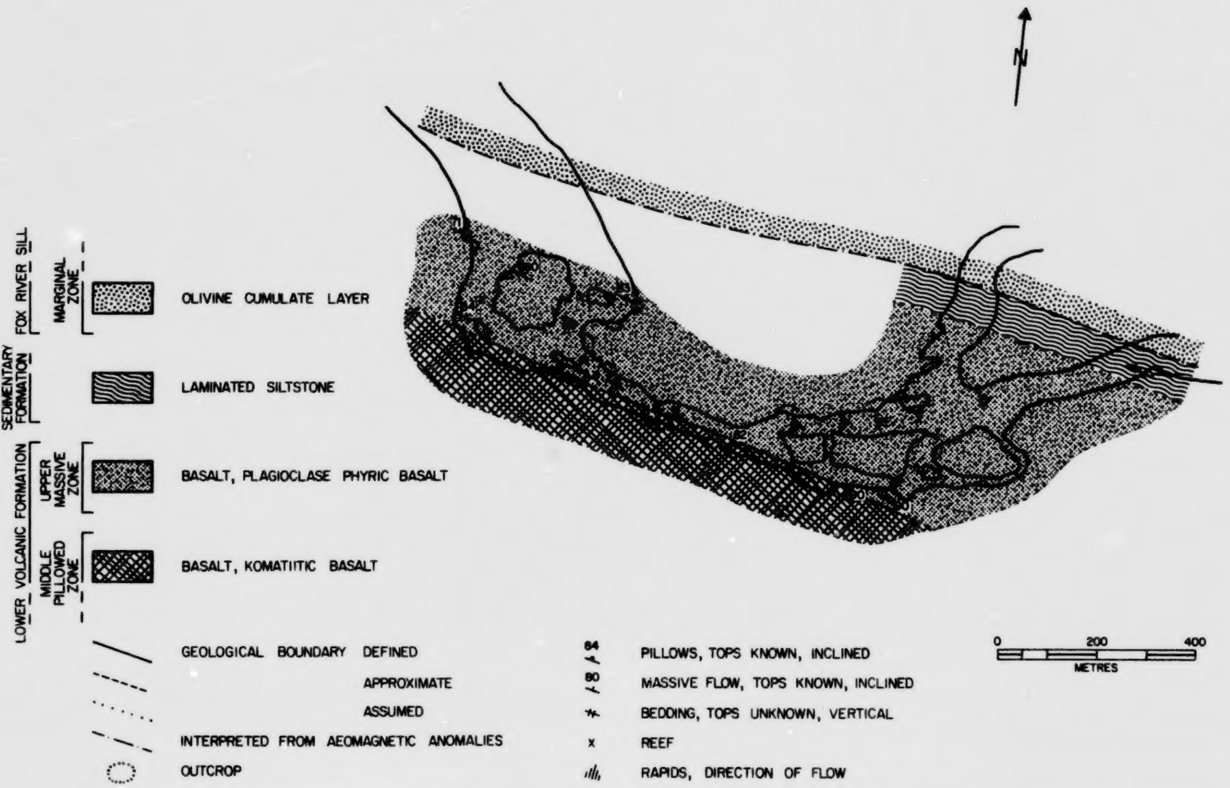
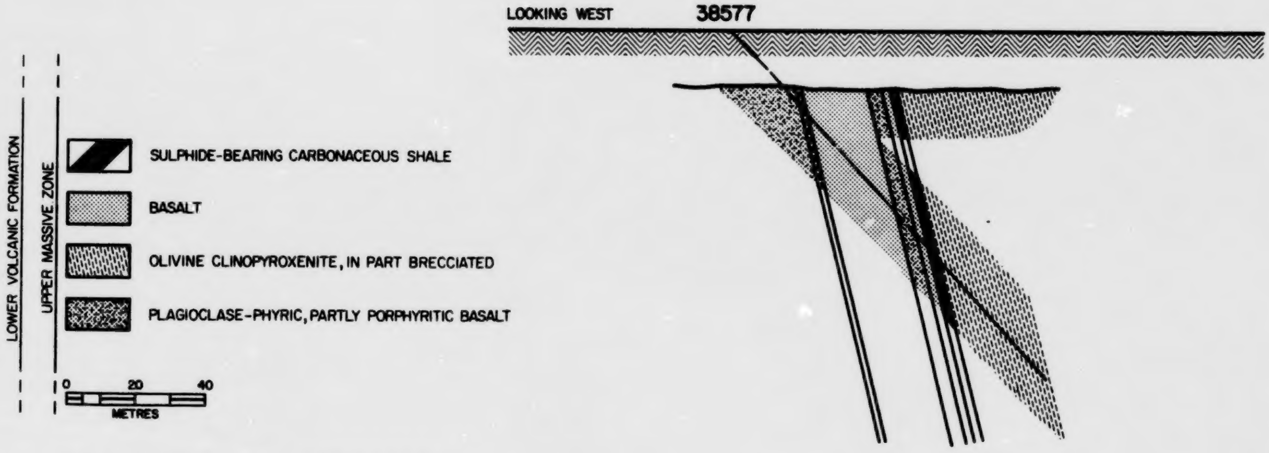

N
FOX RIVER SILL
MARGINAL ZONE
OLIVINE CUMULATE LAYER
MIDDLE SEDIMENTARY FORMATION
LAMINATED SILTSTONE
LOWER VOLCANIC FORMATION
UPPER MASSIVE ZONE
BASALT, PLAGIOCLASE PHYRIC BASALT
MIDDLE PILLOWED ZONE
BASALT, KOMATIITIC BASALT
GEOLOGICAL BOUNDARY DEFINED
APPROXIMATE
ASSUMED
INTERPRETED FROM AEOMAGNETIC ANOMALIES
OUTCROP
84
PILLOWS, TOPS KNOWN, INCLINED
80
MASSIVE FLOW, TOPS KNOWN, INCLINED
BEDDING, TOPS UNKNOWN, VERTICAL
x
REEF
RAPIDS, DIRECTION OF FLOW
0
200
400
METRES

FIGURE 12: Camp Rapids area, Fox River


LOOKING WEST
38577
LOWER VOLCANIC FORMATION
UPPER MASSIVE ZONE
SULPHIDE-BEARING CARBONACEOUS SHALE
BASALT
OLIVINE CLINOPYROXENITE, IN PART BRECCIATED
PLAGIOCLASE-PHYRIC, PARTLY PORPHYRITIC BASALT
0
20
40
METRES

DIP OF UNITS BASED ON CORE AXIS ANGLE OF 28° (1 MEASUREMENT OF LAMINATION IN CARBONACEOUS SHALE)

FIGURE 13: DDH 38577

The rocks are dominantly plagioclase-phyric basalts, and some are porphyritic. They were originally composed of plagioclase-clinopyroxene assemblages in which the original minerals occurred as unsettled crystals. Plagioclase, the dominant phase, occurs as stubby prisms and elongate laths, and is subhedral to euhedral throughout the sequence. Clinopyroxene, on the other hand, occurs as highly irregular shaped grains, that tend to be strongly zoned, and characteristically display wavy extinction; some clinopyroxene is sector zoned (Plate 13). Clinopyroxene displays a slightly brownish colouration which increases in intensity to the north, toward the top of the sequence. Spherulitic and larger poikilitic clinopyroxene crystals distinguish some basalt flows on the Stupart River (Plates 14 and 15). The base of one of these flows is composed of cumulus plagioclase and clinopyroxene crystals (Plate 16).

The porphyritic plagioclase-phyric basalts are characterized by plagioclase phenocrysts (up to 1.5 x 1.0 mm), or clusters of phenocrysts in a fine grained groundmass of subhedral to euhedral plagioclase and irregularly shaped clinopyroxene (Plate 17). Clinopyroxene makes up less than 20 percent of the rocks. The laminations of the concentrically laminated pillows previously described are caused by alternating epidote-carbonate and plagioclase-rich layers. The epidote-carbonate layers are interpreted as being an alteration of original concentric cooling cracks.

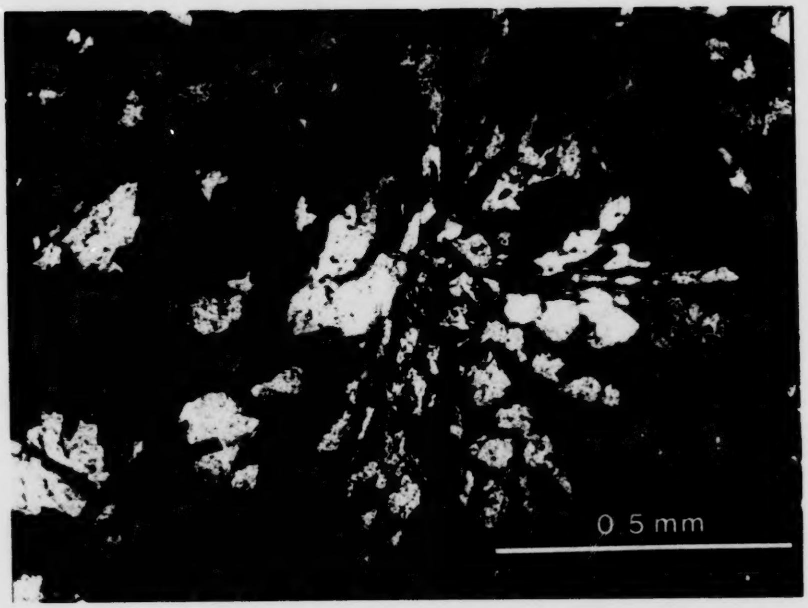
The rocks of the upper massive zone are substantially recrystallized, and the primary textures are not well-preserved. The common secondary assemblage is chlorite, tremolite, epidote and sphene. Albite, quartz, carbonate and muscovite are additional secondary minerals. Pumpellyite is sporadically developed, and is relatively abundant in parts of drill hole 13238. The metamorphic grade ranges from very low grade to lowermost greenschist facies.

The rocks become increasingly more recrystallized to the north or stratigraphically upward, and this is due to the proximity of these rocks to the base of the Fox River Sill. The increase in recrystallization stratigraphically upward in the zone is due to contact metamorphism of these rocks by the Sill. There is no change in the secondary assemblage, apart from an absence of pumpellyite in the rocks of the upper part of the zone, and the increasing recrystallization is characterized by a near total obliteration of the primary assemblage minerals, and their textural relationships.

Pyrrhotite and pyrite are common, though not abundant constituents of the rocks of the upper massive zone.

PLATE 13: Hour-glass zoned clinopyroxene crystal with inclusions of sphene pseudomorphs after coarse grained ilmenite. Base of massive basalt flow, Upper massive zone, Lower volcanic formation, Stupart River section (03-75-71-1) XN.

PLATE 14: Spherulitic clinopyroxene crystal intergrown with plagioclase. Massive basalt flow, Upper massive zone, Lower volcanic formation, Stupart River section (36-75-242-1) XN.



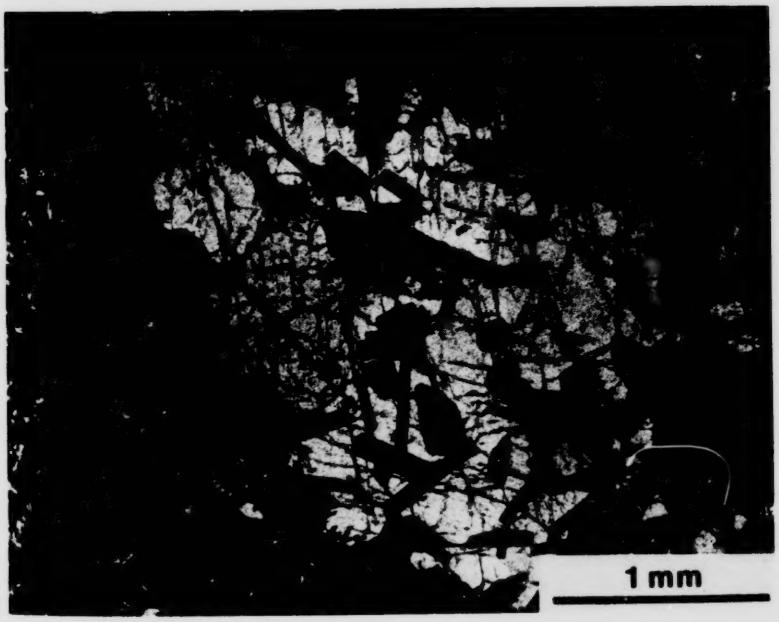
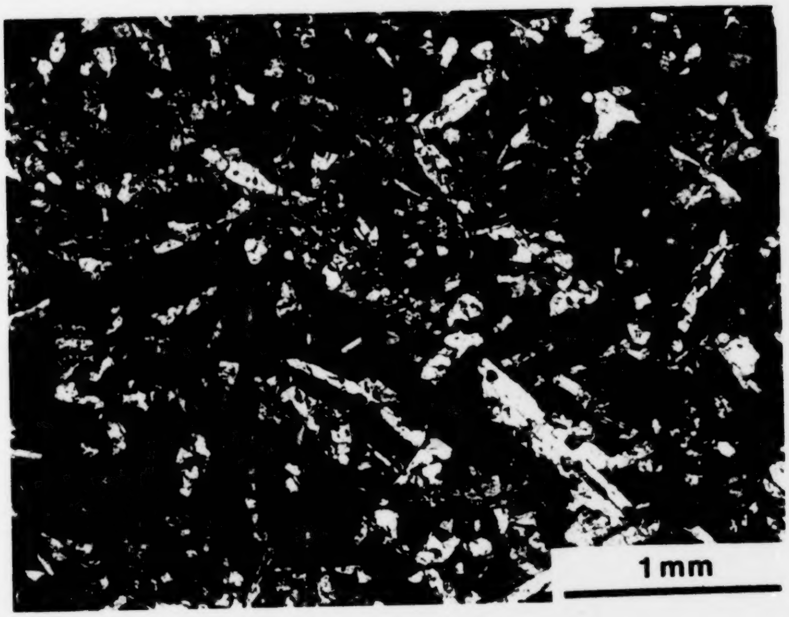


PLATE 15: Irregularly-shaped poikilitic clinopyroxene crystal with inclusions of lath-like plagioclase. Base of massive basalt flow, Upper massive zone, Lower volcanic formation, Stupart River section (03-75-71-1) XN.

PLATE 16: Cumulus plagioclase and clinopyroxene crystals. Base of massive basalt flow, Upper massive zone, Lower volcanic formation, Stupart River section (03-75-70-5) XN.



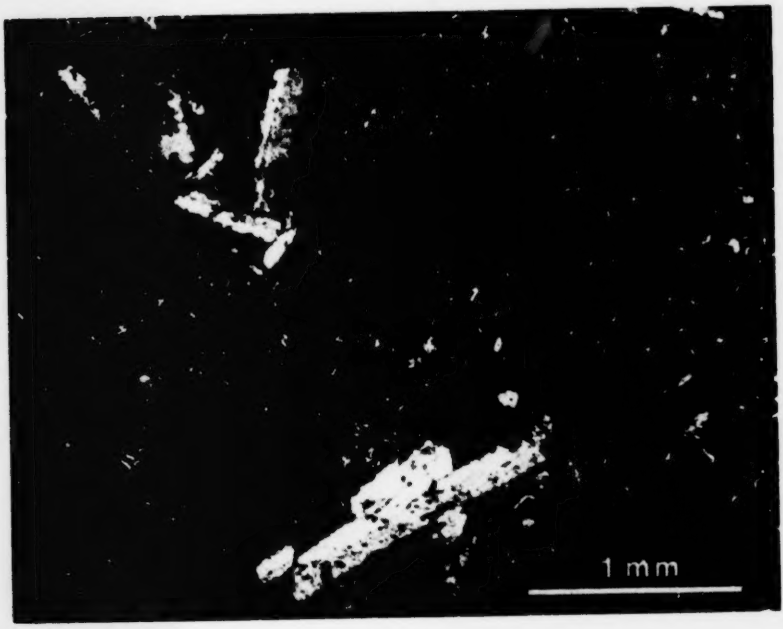
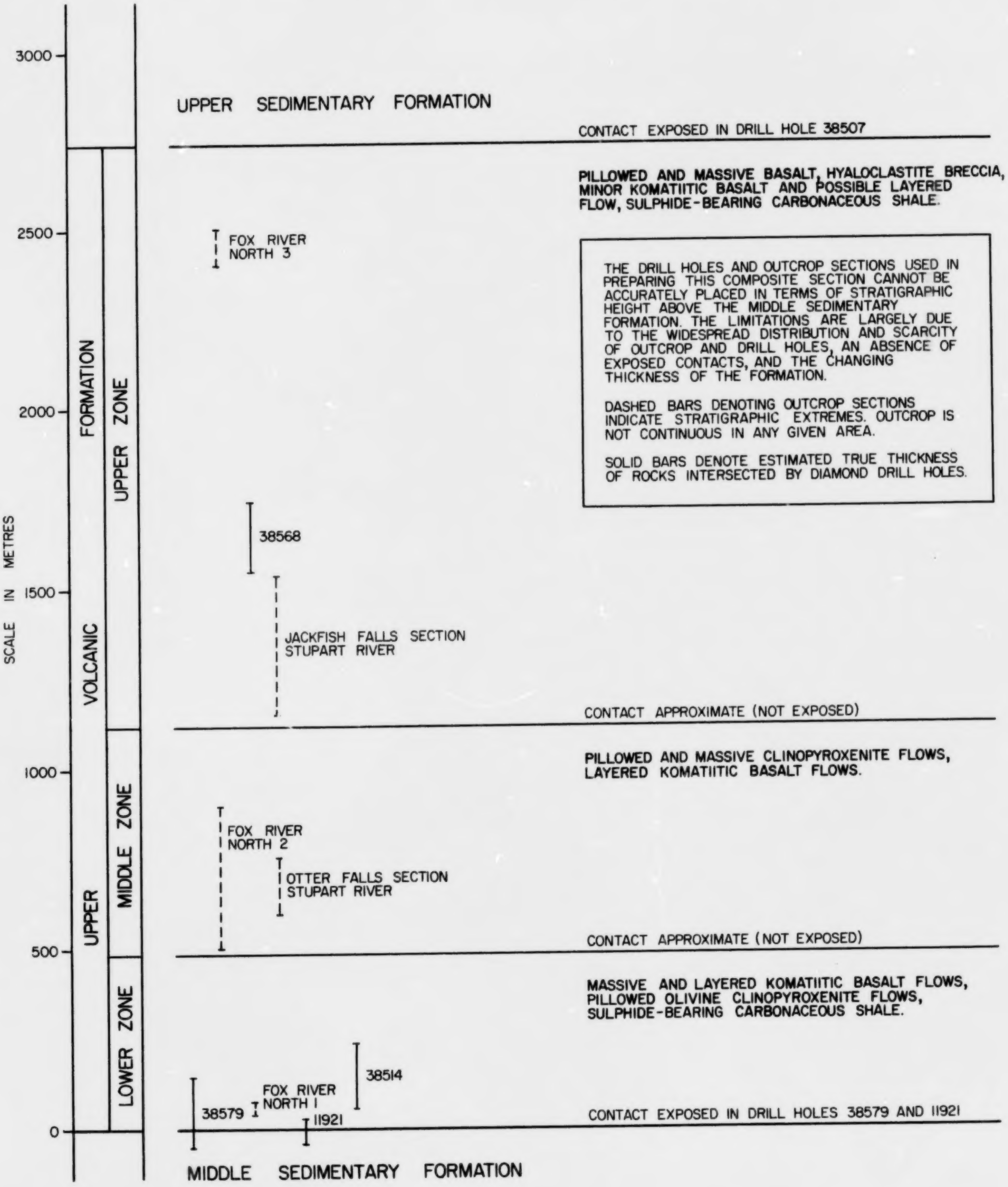


PLATE 17: Plagioclase phenocrysts in a fine grained groundmass composed of plagioclase and clinopyroxene. Pillowed porphyritic basalt, Upper massive zone, Lower volcanic formation, Great Falls section, Fox River (03-69-253) XN.

SUMMARY OF LITHOTEXTURAL AND MINERALOGICAL CHANGES WITH STRATIGRAPHIC HEIGHT

Rocks of the Lower volcanic formation display a progressive change in composition and textural character upward in the sequence. Olivine-rich cumulus rocks occur in the differentiated, layered flows of the lower massive zone. The layered flows are intercalated with komatiitic basalt and basalt flows. The flows of the middle pillowed zone range from plagioclase-bearing olivine clinopyroxenite near the base to basalt at the top. The flows of the upper massive zone are dominantly plagioclase-phyric basalts. The rocks of the three zones are considered to represent a consanguineous suite of successive eruptions since there appears to be no indication of a significant hiatus within the formation. The initial eruptions ranged from basalt to more mafic and ultramafic flows. Some flows were relatively ultramafic in character as indicated by the olivine cumulate zone of layered flows, and the pyroxene spinifex zone of komatiitic basalt flows. The fluid portion of these flows may have been clinopyroxenitic in composition as indicated by the pyroxene-rich margins of the layered flows. It is not known whether the olivine of the layered flow olivine cumulate zones crystallized after or before eruption of the fluid phase; however, hopper-shaped olivine, in the plagioclase-bearing olivine clinopyroxenites of the basal part of the middle pillowed zone, indicates that olivine was a liquidus phase in those rocks. Toward the top of the pillowed zone, skeletal plagioclase crystals in an altered glass matrix attest that plagioclase became a liquidus phase. The abundance of plagioclase in rocks of the upper massive zone has been previously noted.

The flows of the Lower volcanic formation appear to have been derived from fluids that became more highly evolved with time. Derivation of these fluids from a differentiating magma seems a reasonable proposal, and for this reason the lower differentiated intrusions are considered a likely source. The process proposed is one where a part of the fluid portion of the intrusion periodically breaches the roof of the chamber and reaches the surface during differentiation. In this fashion the first phase to breach the roof and reach the surface could have been pyroxenitic in composition, and could have contained suspended olivine crystals. Successive fluids to reach the surface would be more highly evolved because of continued differentiation in the intrusion chamber. The overall change in composition of the flows of the formation from base to top is, therefore, considered to be directly related to differentiation of the lower differentiated intrusions. The intercalated basalt flows in the lower massive zone do not appear to be significantly abundant and may represent lava from another, nearby source.



3000
2500
2000
1500
1000
500
0
SCALE IN METRES
UPPER VOLCANIC FORMATION
UPPER ZONE
MIDDLE ZONE
LOWER ZONE
UPPER SEDIMENTARY FORMATION
CONTACT EXPOSED IN DRILL HOLE 38507
FOX RIVER NORTH 3
38568
JACKFISH FALLS SECTION STUPART RIVER
CONTACT APPROXIMATE (NOT EXPOSED)
FOX RIVER NORTH 2
OTTER FALLS SECTION STUPART RIVER
CONTACT APPROXIMATE (NOT EXPOSED)
38514
FOX RIVER NORTH 1
38579
11921
CONTACT EXPOSED IN DRILL HOLES 38579 AND 11921
MIDDLE SEDIMENTARY FORMATION

PILLOWED AND MASSIVE BASALT, HYALOCLASTITE BRECCIA, MINOR KOMATIITIC BASALT AND POSSIBLE LAYERED FLOW, SULPHIDE-BEARING CARBONACEOUS SHALE.

THE DRILL HOLES AND OUTCROP SECTIONS USED IN PREPARING THIS COMPOSITE SECTION CANNOT BE ACCURATELY PLACED IN TERMS OF STRATIGRAPHIC HEIGHT ABOVE THE MIDDLE SEDIMENTARY FORMATION. THE LIMITATIONS ARE LARGELY DUE TO THE WIDESPREAD DISTRIBUTION AND SCARCITY OF OUTCROP AND DRILL HOLES, AN ABSENCE OF EXPOSED CONTACTS, AND THE CHANGING THICKNESS OF THE FORMATION.

DASHED BARS DENOTING OUTCROP SECTIONS INDICATE STRATIGRAPHIC EXTREMES. OUTCROP IS NOT CONTINUOUS IN ANY GIVEN AREA.

SOLID BARS DENOTE ESTIMATED TRUE THICKNESS OF ROCKS INTERSECTED BY DIAMOND DRILL HOLES.

PILLOWED AND MASSIVE CLINOPYROXENITE FLOWS, LAYERED KOMATIITIC BASALT FLOWS.

MASSIVE AND LAYERED KOMATIITIC BASALT FLOWS, PILLOWED OLIVINE CLINOPYROXENITE FLOWS, SULPHIDE-BEARING CARBONACEOUS SHALE.

FIGURE 14: Composite section, Upper volcanic formation

UPPER VOLCANIC FORMATION

GENERAL STATEMENT

Rocks of the Upper volcanic formation have been examined in five outcrop areas, and four diamond drill holes (Fig. 3). In addition, Inco logs of four drill holes that penetrate Upper volcanic formation rocks in the western part of the area (Fig. 3) have been utilized, although the core itself was not examined. The northernmost hole of the four is interpreted to have intersected the contact between volcanic rocks of the Upper volcanic formation, and shales of the Upper sedimentary formation. The contact between rocks of the Middle sedimentary formation, and the Upper volcanic formation has been observed in drill holes 38579 and 11921 (Figs. 15 and 16). The Upper volcanic formation ranges from approximately 2 500 to 3 500 m thick, and rocks of the formation are known along a strike length of approximately 40 km.

The composite stratigraphic section (Fig. 14) is less reliable than that for the Lower volcanic formation because there is little overlap of units in the outcrop areas and drill holes used to prepare the section. Despite this less reliable nature, it is clear from the disposition of units that the Upper and Lower volcanic formations display a similar change from ultramafic to mafic flows from base to top.

The Upper volcanic formation consists of a lower zone of layered differentiated flow units and komatiitic basalt flows, a middle zone of pillowed olivine clinopyroxenite and massive and layered flows, and an upper zone of massive and pillowed basalt. Sulphide-bearing carbonaceous shale is a common, though not abundant, interflow sedimentary rock.

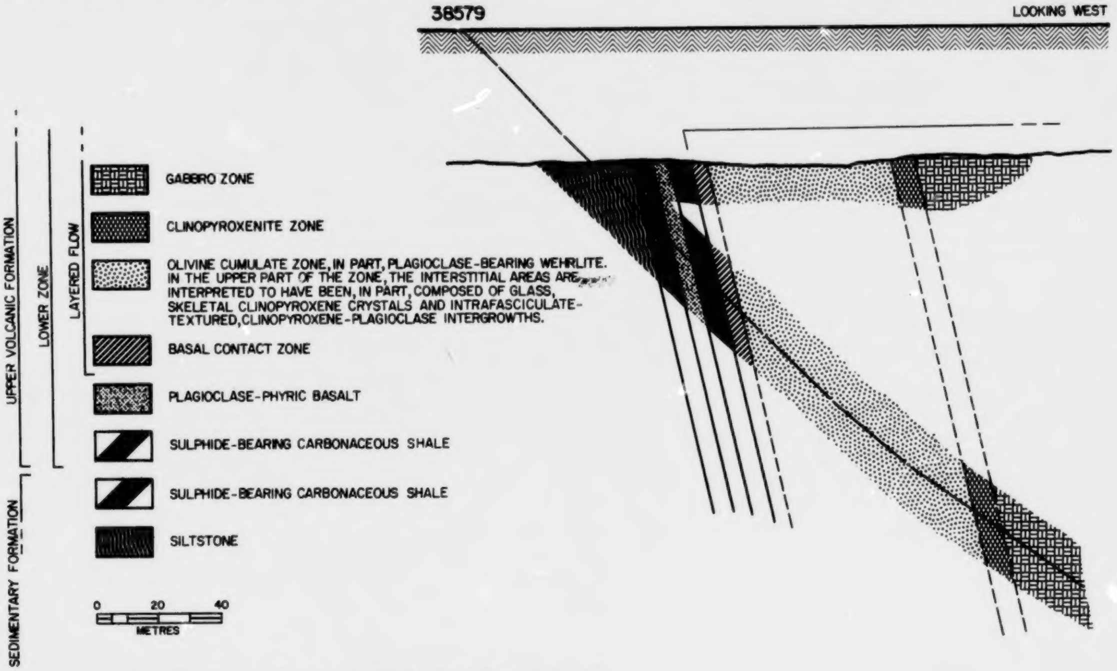
Primary volcanic structures are perfectly preserved in outcrop, and top directions can be readily determined. Flow tops face north, and south-facing tops have not been identified. The distribution of units in layered and composite flows in drill core also indicate north-facing sequences. The flows strike westerly to northwesterly and dip steeply north. There is an absence of fabric in the rocks, as well as an absence of folding, apart from a general rotation of the sequence of approximately 80° about a westerly to northwesterly axis.

The rocks of the Upper volcanic formation are substantially less recrystallized than their counterparts in the Lower volcanic formation. This is manifest in the widespread distribution of pumpellyite and prehnite, in the excellent state of preservation of clinopyroxene, and in the rare preservation of original basic plagioclase. The trend toward less recrystallized rocks with increasing stratigraphic height observed in Lower volcanic formation rocks appears to hold true for the Upper volcanic formation.

LOWER ZONE

DRILL HOLE 38579

The uppermost 6 m of the Middle sedimentary formation is characterized by sulphide-bearing carbonaceous shale. A 5.5 m, vesiculated, plagioclase-phyric basalt flow is the first extrusive rock encountered, and this in turn is overlain by 6 m of sulphide-bearing carbonaceous shale. The contact between rocks of the Middle sedimentary formation and rocks of the Upper volcanic formation is placed at the base of the plagioclase-phyric flow (Fig. 15). A layered, differentiated sequence, ranging from peridotite to gabbro in com-


38579
LOOKING WEST
UPPER VOLCANIC FORMATION
LOWER ZONE
LAYERED FLOW
GABBRO ZONE
CLINOPYROXENITE ZONE
OLIVINE CUMULATE ZONE, IN PART, PLAGIOCLASE-BEARING WEHRLITE. IN THE UPPER PART OF THE ZONE, THE INTERSTITIAL AREAS ARE INTERPRETED TO HAVE BEEN, IN PART, COMPOSED OF GLASS, SKELETAL CLINOPYROXENE CRYSTALS AND INTRAFASCICULATE-TEXTURED, CLINOPYROXENE-PLAGIOCLASE INTERGROWTHS.
BASAL CONTACT ZONE
PLAGIOCLASE-PHYRIC BASALT
SULPHIDE-BEARING CARBONACEOUS SHALE
SULPHIDE-BEARING CARBONACEOUS SHALE
SILTSTONE
MIDDLE SEDIMENTARY FORMATION
0
20
40
METRES

DIP OF UNITS BASED ON CORE AXIS ANGLE OF 32°(AVERAGE LAMINATION OF SILTSTONE)

FIGURE 15: DDH 38579

position, overlies the carbonaceous shale. Four zones, similar to those of the layered flows of the Lower volcanic formation, are penetrated by drill hole 38579. An original pyroxene-plagioclase-olivine assemblage, now substantially altered to tremolite-chlorite, forms a 4.8 m marginal zone. This is overlain by a 58 m olivine cumulate zone, the lower part of which was originally plagioclase-bearing wehrlite. The upper part of the zone consists of cumulus, euhedral olivine, with sharp terminations, in a groundmass of featureless serpentine containing numerous, fine grained, skeletal clinopyroxene crystals (Plates 18 and 19). The featureless serpentine areas are interpreted as representing altered glass. One sample consists of cumulus olivine in a groundmass composed of radiating sprays of serpentine and amphibole, that renders a texture that is similar to the intrafasciculate texture previously described. Fine grained, euhedral chromite is an ubiquitous phase in the zone. The rocks have been substantially altered to serpentine ± chlorite ± tremolite. A 7 m thick clinopyroxenite zone separates the olivine cumulate zone from the overlying gabbro zone. The cumulus clinopyroxenes are twinned and zoned, some of the crystals displaying hour-glass and sector zones. Cumulus clinopyroxenes and plagioclase are the dominant minerals of the gabbro zone, and large, trellis-like ilmenite crystals, that are largely altered to sphene, are common. The cumulus textures give way to complex textures between clinopyroxene and plagioclase, in which the clinopyroxene forms gently curving skeletal-like masses with splayed, divergent terminations. Some clinopyroxenes are nearly spherulitic, whereas others that are dendritic form long, slender crystals with numerous short curving branches (Plates 20 and 21). Plagioclase occurs as optically continuous grains, that occupy the hollow spaces within the individual clinopyroxene crystals. This textural relationship is the inverse of that previously described in which plagioclase forms irregular skeletal, spherulitic crystals, and clinopyroxene occupies the hollow spaces within the individual plagioclase crystals. The nature of the clinopyroxene suggests rapid crystallization from a supercooled liquid. The presence of skeletal clinopyroxene and possible altered glass in the olivine cumulate zone, and spherulitic and dendritic clinopyroxene in the upper part of the gabbro zone, suggests that this layered sequence had an extrusive origin. Unfortunately, the top of this sequence is not penetrated by the drill hole so the presence of a flow top cannot be documented. The lowermost part of the Upper volcanic formation contains plagioclase-phyric and possible layered flows.

DRILL HOLE 11921

Drill hole 11921 (Fig. 16) intersects quartz-rich siltstone, now substantially recrystallized to hornfels, of the upper part of the Middle sedimentary formation, and a differentiated sill, composed of a lower peridotite zone (originally plagioclase-bearing lherzolite), and an upper gabbro zone. The rocks are cumulus, and orthopyroxene was an original constituent of the peridotite. There are no unusual textures, and the sequence is considered to be intrusive. The lowermost part of the Lower volcanic formation consists of rocks that display fine grained, complex intergrowths between plagioclase and clinopyroxene, as well as elongate clinopyroxene crystals, and sheaf-like masses of acicular plagioclase crystals (Plate 22). The presence of vesicles, and the textural features are interpreted as indicating that the rocks are extrusive, and komatiitic basalt in composition. Sulphide-bearing carbonaceous shale separates successive flows.

FOX RIVER NORTH 1 SECTION

Parts of a layered flow are exposed in Fox River north 1 section (Fig. 17). A medium grained, olivine-rich zone of unknown thickness is overlain by an 8 m thick, medium grained, transition zone, that is in turn overlain by a 6 m thick, pyroxene spinifex-bearing, vesiculated flow top. A gabbroic rock, with a texture similar to that of the transition zone, may represent the basal margin of the flow. Pillowed olivine clinopyroxenite underlies the massive flow which is between 18 m and 34 m thick.

Skeletal clinopyroxene crystals, many as skeletal crystal segments having a distinctive M-shape or bat wing-shape, characterize the rocks of the flow top zone (Plate 23). The segments occur as very fine grained (<0.1 mm) randomly dispersed elements. In some cases, numerous segments combine to form straight, delicate, ornamental chain-like crystals, up to 3 mm long. Some individual skeletal segments are much coarser grained (up to 1 mm), and occur as clusters or aggregates (Plate 24). They appear to represent a partly settled, suspended phase in a finer grained groundmass. The sporadic distribution of these coarser grained clusters contributes to the overall heterogeneous nature of the flow top zone. Plagioclase commonly forms delicate, straight to slightly curving, acicular crystals that are parallel to subparallel over several millimetres. Some very fine grained clinopyroxene is intergrown with the plagioclase in a sporadic fashion. This morphological variety of plagioclase may represent a spinifex-like growth. Plagioclase also forms distinctly spherulitic crystals with splayed, divergent terminations. Clinopyroxene occupies the hollow spaces in the spherulitic plagioclase.

Clinopyroxene spinifex defines a texture characterized by elongate clinopyroxene crystals arranged in partly radiating arrays (Plates 25 and 26). Each elongate crystal is formed by the coupling of numerous skeletal clinopyroxene segments, and the crystals are therefore skeletal in nature. Individual crystals are up to 6 mm long, and the texture is megascopically visible. The goundmass consists of very fine grained, acicular plagioclase in subparallel to parallel development as previously described. Olivine, some of which originally occurred as hopper-or lantern-shaped crystals, was an original constituent. It has been replaced by chlorite and quartz. Vesicles have been filled by a variety of minerals, the most abundant being quartz, chlorite, carbonate and prehnite. Prehnite and pumpellyite are sporadically distributed through the zone.

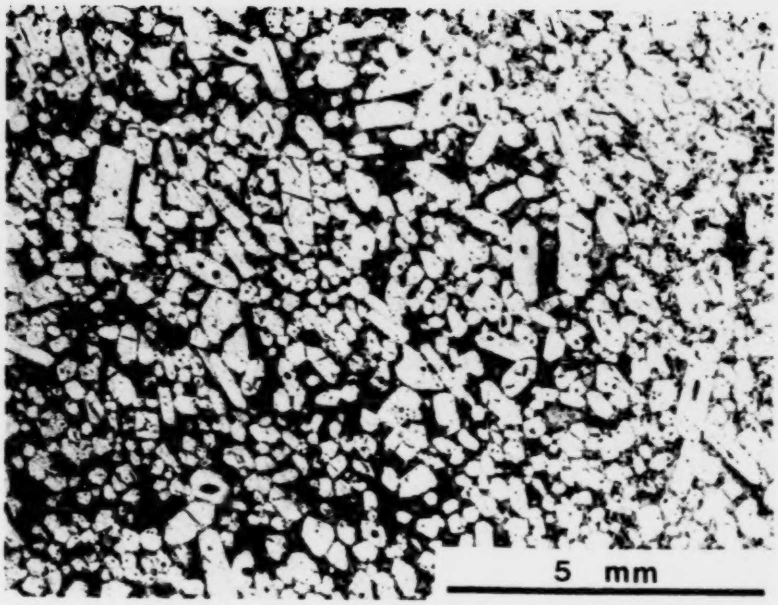


PLATE 18: Olivine cumulate zone of layered flow. The texture is well-preserved although the rock is composed almost entirely of serpentine. The groundmass was composed of skeletal clinopyroxene crystals and glass. Some of the olivine crystals have been embayed by the groundmass. Olivine cumulate zone, layered flow, Lower zone, Upper volcanic formation, DDH 38579 (38579-640) PL.

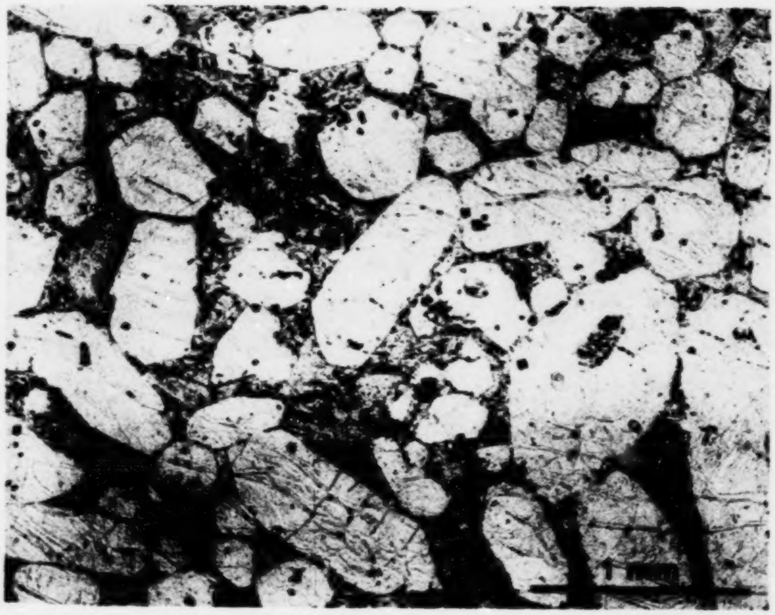
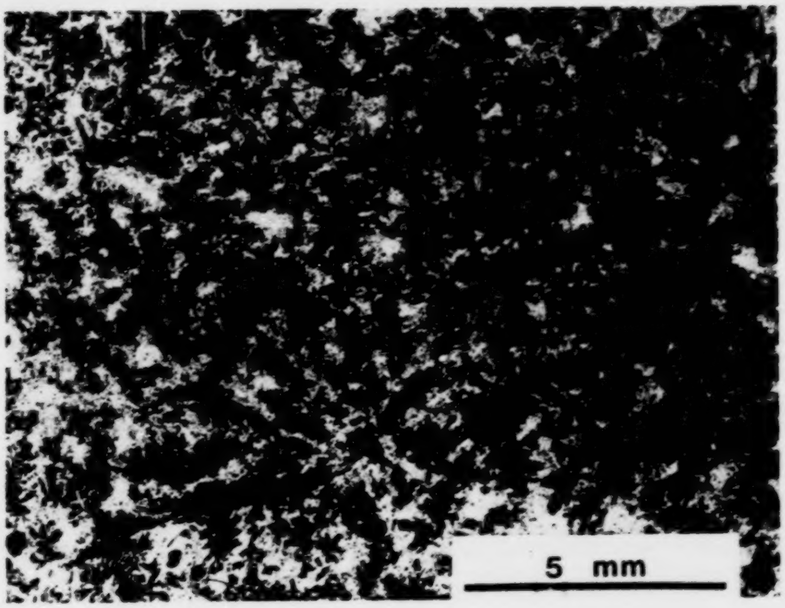


PLATE 19: Detail of olivine cumulate zone of layered flow. Interstitial areas between olivine crystals are composed of skeletal clinopyroxene crystals and featureless glass both of which have been converted to serpentine. Irregular opaque patches are magnetite, euhedral opaque crystals are chromite. Olivine cumulate zone, layered flow, Lower zone, Upper volcanic formation, DDH 38579 (38579-650) PL.

PLATE 20: Gabbro zone, layered flow. Note curving, branching dendritic to spherulitic clinopyroxene crystals. Each clinopyroxene crystal is continuous and is intergrown with plagioclase forming a complex intrafasciculate texture. Opaque minerals are pyrrhotite, and sphene replacing ilmenite. Gabbro zone, layered flow, Lower zone, Upper volcanic formation, DDH 38579 (38579-860) PL.



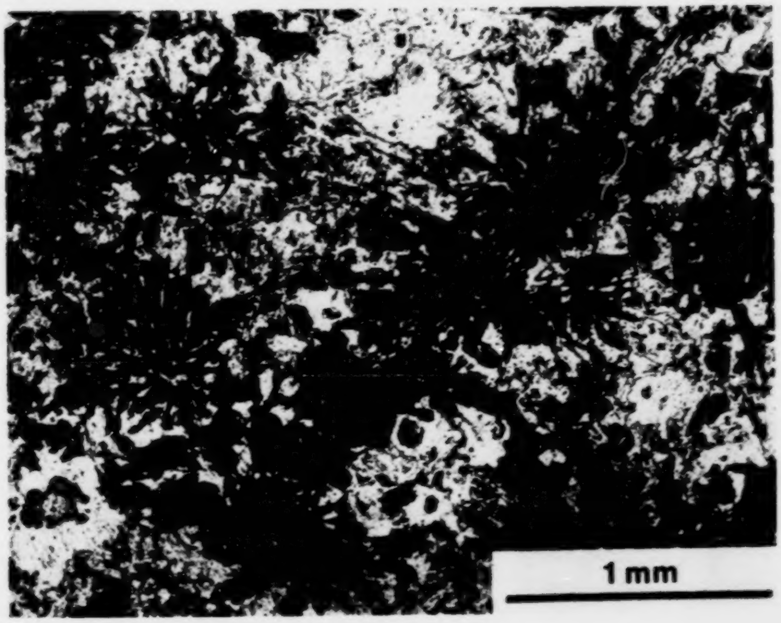
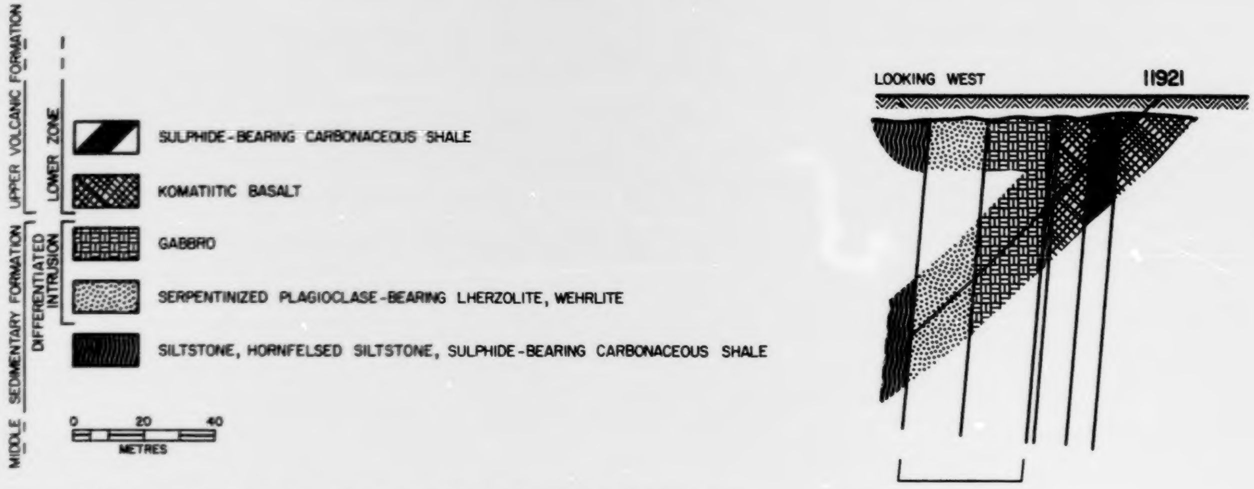


PLATE 21: Detail of dendritic and spherulitic clinopyroxene crystals seen in Plate 20 PL.


UPPER VOLCANIC FORMATION
LOWER ZONE
MIDDLE SEDIMENTARY FORMATION
DIFFERENTIATED INTRUSION
SULPHIDE-BEARING CARBONACEOUS SHALE
KOMATIITIC BASALT
GABBRO
SERPENTINIZED PLAGIOCLASE-BEARING LHERZOLITE, WEHRLITE
SILTSTONE, HORNFELSED SILTSTONE, SULPHIDE-BEARING CARBONACEOUS SHALE
0
20
40
METRES
LOOKING WEST
11921

DIP OF UNITS BASED ON CORE AXIS ANGLE OF 40° (1 MEASUREMENT OF LAYERING IN SILTSTONE)

FIGURE 16: DDH 11921

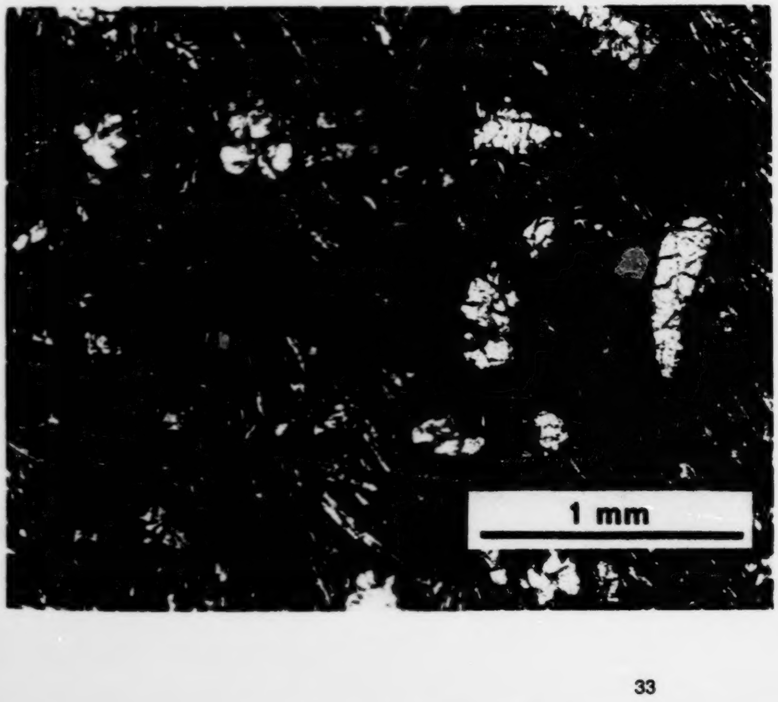


PLATE 22: Clinopyroxene as suspended blades and irregular crystals in a groundmass dominated by very fine grained plagioclase laths. The plagioclase laths occur as groups of subparallel crystals and some are arranged in fan-like arrays. The resulting pattern is similar but on a finer scale to the pattern of clinopyroxene that gives rise to clinopyroxene spinifex texture. Komatiitic basalt flow, Lower zone, Upper volcanic formation, DDH 11921 (11921-50) XN.

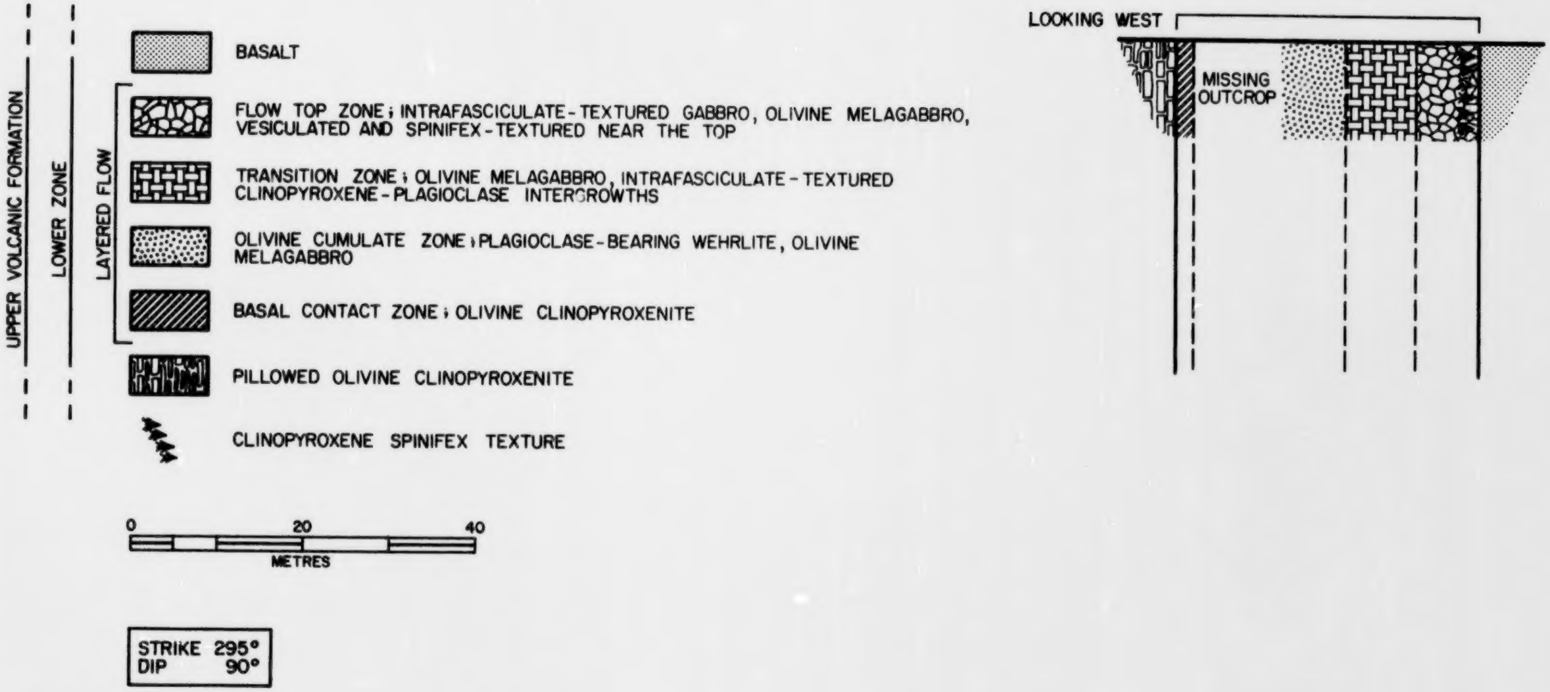
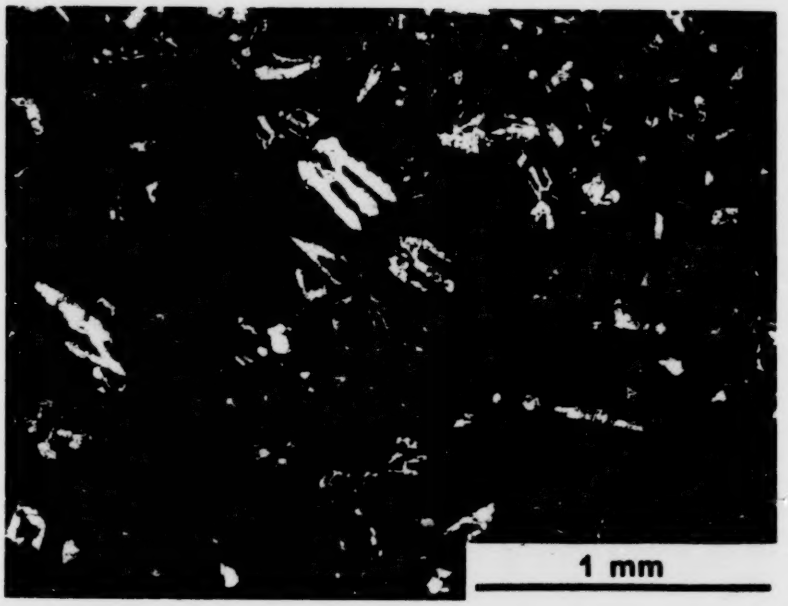

LOOKING WEST
MISSING OUTCROP
UPPER VOLCANIC FORMATION
LOWER ZONE
LAYERED FLOW
BASALT
FLOW TOP ZONE; INTRAFASCICULATE-TEXTURED GABBRO, OLIVINE MELAGABBRO, VESICULATED AND SPINIFEX-TEXTURED NEAR THE TOP
TRANSITION ZONE; OLIVINE MELAGABBRO, INTRAFASCICULATE-TEXTURED CLINOPYROXENE-PLAGIOCLASE INTERGROWTHS
OLIVINE CUMULATE ZONE; PLAGIOCLASE-BEARING WEHRLITE, OLIVINE MELAGABBRO
BASAL CONTACT ZONE; OLIVINE CLINOPYROXENITE
PILLOWED OLIVINE CLINOPYROXENITE
CLINOPYROXENE SPINIFEX TEXTURE
0
20
40
METRES
STRIKE 295°
DIP 90°

FIGURE 17: Fox River north 1 section

PLATE 23: Suspended, randomly oriented, clinopyroxene skeletal segments. Groundmass is composed of fine grained needles and fibre-like plagioclase crystals, some of which are arranged in fan-like arrays. Flow top zone, layered flow, Lower zone, Upper volcanic formation, Fox River north 1 section, Fox River (03-75-57-4) XN.



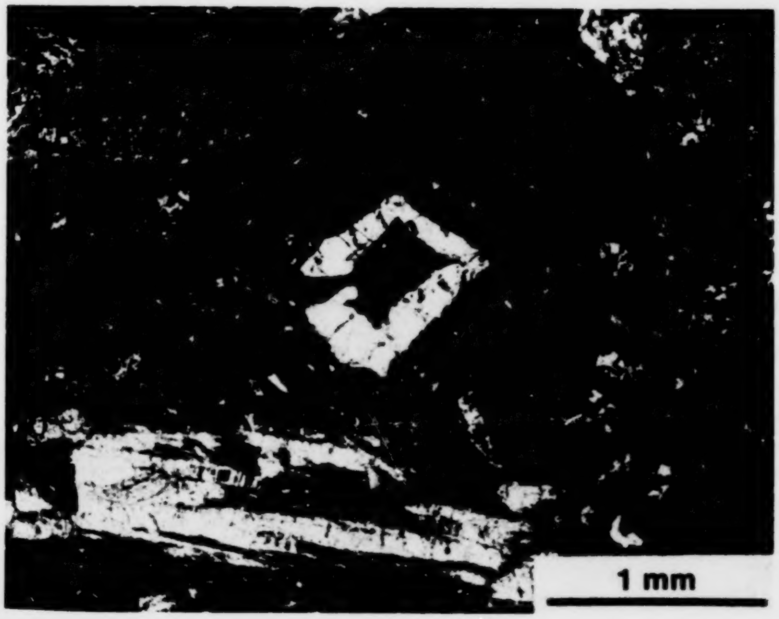


PLATE 24: Detail of suspended, skeletal clinopyroxene crystals. Note hollow cores of near basal sections. Suspended polygonal and granular olivine crystals also occur. Groundmass is composed of intrafasciculate-textured intergrowth between fine grained plagioclase laths and clinopyroxene crystals. Flow top zone, layered flow, Lower zone, Upper volcanic formation, Fox River north 1 section (03-75-57-5) XN.

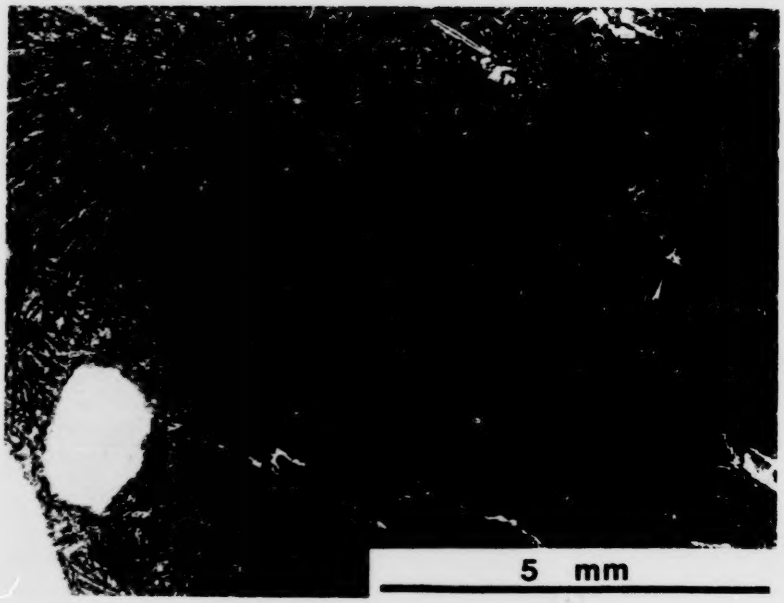


PLATE 25: Clinopyroxene spinifex texture defined by sprays of elongate, ornamental chain clinopyroxene crystals. Individual crystals are up to 6 mm long. Groundmass is composed of fine grained needles and fibre-like plagioclase crystals, some of which are arranged in fan-like arrays. Note carbonate-filled vesicle. Flow top, layered flow, Lower zone, Upper volcanic formation, Fox River north 1 section, Fox River (36-75-230-1e) PL.

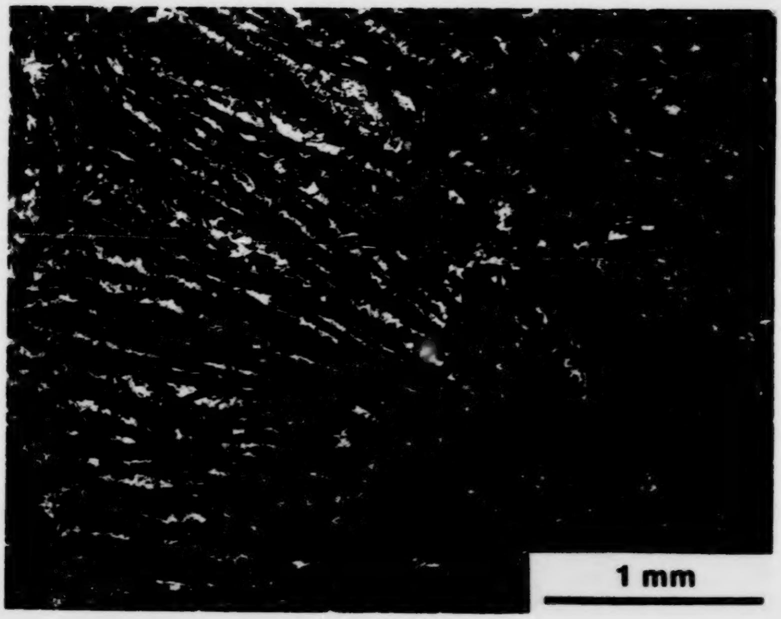


PLATE 26: Detail of clinopyroxene spinifex texture. Note well-developed fan-like array of elongate clinopyroxene crystals. Flow top, layered flow, Lower zone, Upper volcanic formation, Fox River north 1 section, Fox River (36-75-230-1e) PL.

The contact between the flow top zone and transition zone is gradational. The transition zone is characterized by medium grained olivine and clinopyroxene, up to 1.5 and 3.0 mm, respectively, in a much finer grained groundmass, distinguished by slender spherulitic plagioclase complexly intergrown with clinopyroxene. The combination of medium grained, partly settled olivine and skeletal clinopyroxene, and the fine grained groundmass dominated by spherulitic plagioclase renders an unusual textural character to the rock (Plate 27). The transition zone forms a transition between the flow top and the underlying olivine cumulate zone. The settled clinopyroxene is medium grained yet retains its skeletal habit (Plate 28). Clusters of semi-translucent, red-brown chromite crystals are associated with some of the altered olivines. Olivine has been pseudomorphously replaced by chlorite, quartz, and tremolite. In some rocks, plagioclase has been pseudomorphously converted to an extremely fine grained, isotropic matte of chlorite. Sphene, pseudomorphously replacing original skeletal ilmenite crystals is common.

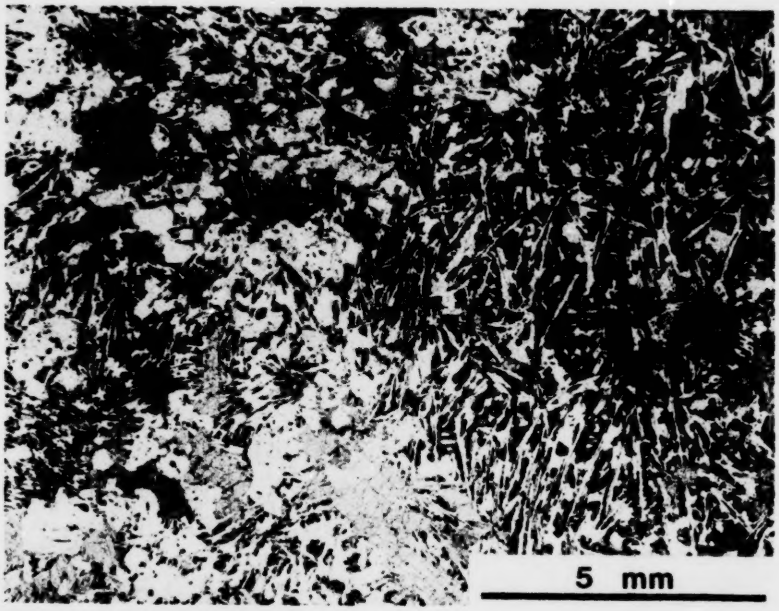


PLATE 27: Transition zone of layered flow. Rock is composed of partly cumulus (suspended) olivine as clusters of polyhedral crystals and partly cumulus (suspended) skeletal clinopyroxene in a matrix distinguished by intrafasciculate-textured clinopyroxene and plagioclase. The ratio of suspended crystals to matrix is highly variable. Transition zone, layered flow, Lower zone, Upper volcanic formation, Fox River north 1 section, Fox River (03-75-57-6) PL.

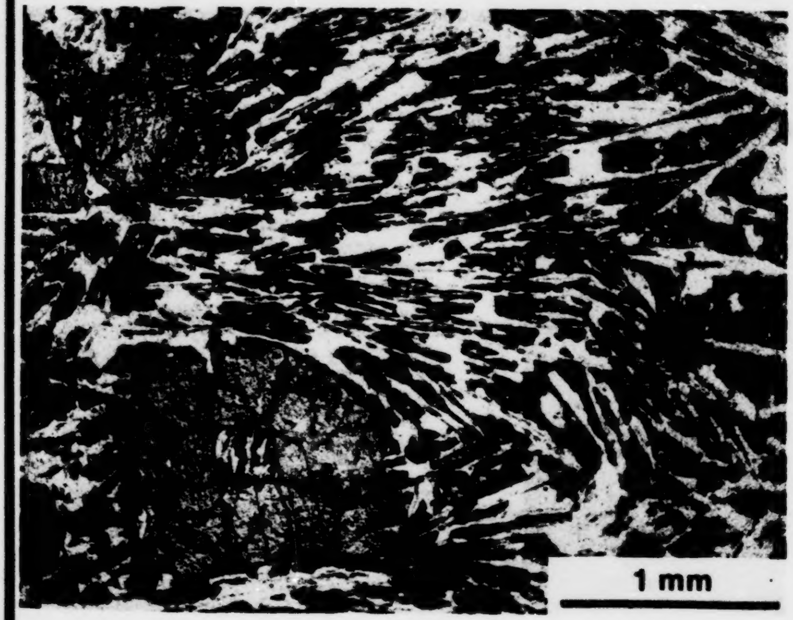


PLATE 28: Transition zone of layered flow. Rock consists of partly settled polyhedral olivine and skeletal clinopyroxene in a matrix characterized by subradially disposed plagioclase laths intergrown with clinopyroxene, forming an intrafasciculate texture. The original plagioclase and olivine have been replaced by a finely woven chlorite matte. Note the hollow core of the basal clinopyroxene section occupied by matrix material. Transition zone, layered flow, Lower zone, Upper volcanic formation, Fox River north 1 section, Fox River (03-75-57-6) PL.

The contact between the transition zone and underlying olivine-rich zone is gradational over 1 m. The olivine cumulate zone contains fine grained olivine (0.5 mm long axis average dimension), and minor clinopyroxene in a groundmass, that ranges from altered basic glass containing skeletal clinopyroxene segments, to spherulitic plagioclase-clinopyroxene intergrowths (Plate 29). Olivine, which ranges up to 60 percent in abundance, has been completely replaced by tremolite, and fine grained chlorite and serpentine. Rock types range from plagioclase-bearing wehrlite to olivine melagabbro. Clusters of semi-transcluent, red-brown chromite crystals have a sporadic distribution.

ORIGIN OF FOX RIVER NORTH 1 LAYERED FLOW

The flow exposed in Fox River north 1 section is similar to layered flows previously described. It differs, however, in lacking successive differentiated layers, such as a clinopyroxenite zone, and its transition zone forms a transition between the fine-grained flow top and the olivine cumulate zone. The flow likely originated in a fashion similar to other layered flows, through extrusion of lava, and settling of olivine crystals to form the cumulus olivine-rich zone (Fig. 18). Skeletal, hopper-or lantern-shaped olivine crystals in the flow top suggest that olivine was capable of crystallizing from the fluid phase. However, the extent to which olivine was a suspended phase prior to extrusion, versus its possible crystallization after extrusion, is not known. In the upper part of the flow, delicate, skeletal, clinopyroxene segments and clinopyroxene spinifex represent incipient nucleation of clinopyroxene. Settling of some segments took place giving rise to medium grained, skeletal clinopyroxene crystals in the flow top and transition zones. Subsequent rapid crystallization of plagioclase is indicated by the spinifex-like, subparallel, straight to slightly curving, acicular crystals, and the spherulitic crystals displaying splayed divergent terminations. The presence of pyroxene spinifex and hopper olivine, and the abundance of cumulus olivine indicate that the liquid was very basic, perhaps pyroxenite in composition, when it was erupted. The presence of chromite indicates an ultramafic parentage for the flow.

DRILL HOLE 38514

Drill hole 38514 (Fig. 19) intersects a succession of komatiitic basalt flows and layered flows, ranging from 6 to 55 m thick. Sulphide-bearing carbonaceous shale forms thin (up to 4 m) horizons separating successive flows.

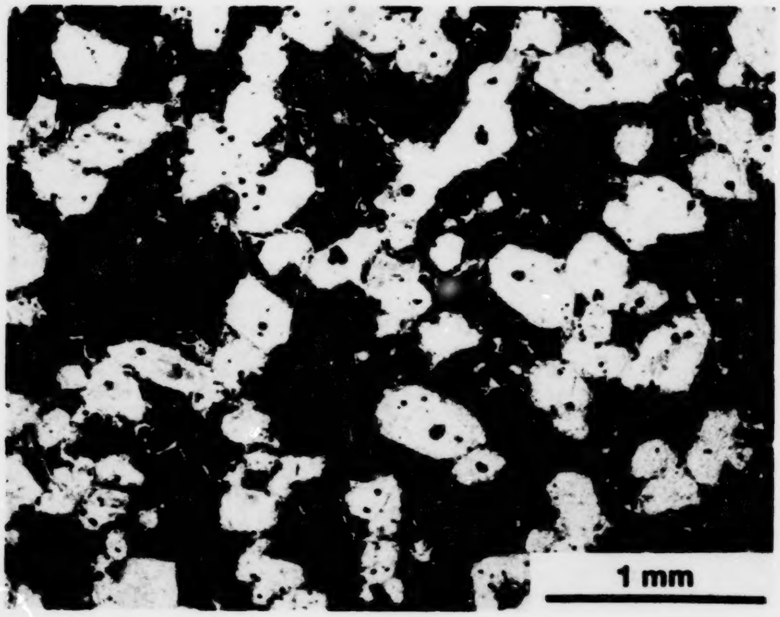


PLATE 29: Partly cumulus (suspended) polyhedral olivine crystals. Olivine has been replaced by a fine grained intergrowth of tremolite, talc, serpentine and chlorite ± magnetite. M- and bat wing-shaped skeletal clinopyroxene crystals are enclosed in altered glass. The opaque minerals are dominantly magnetite, although pyrrhotite and euhedral chromite occur. The original glass has altered to a very fine grained matte of fibrous amphibole. Olivine cumulate zone, layered flow, Lower zone, Upper volcanic formation, Fox River north 1 section, Fox River (03-75-57-7) PL.

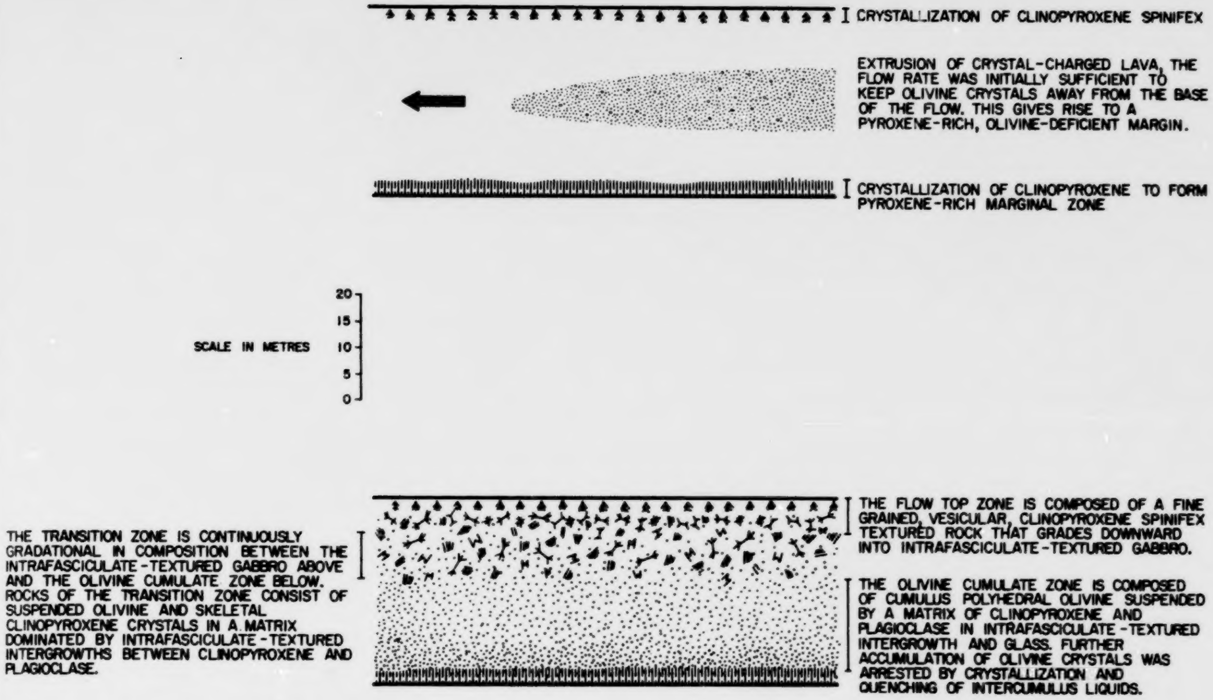

CRYSTALLIZATION OF CLINOPYROXENE SPINIFEX
EXTRUSION OF CRYSTAL-CHARGED LAVA, THE FLOW RATE WAS INITIALLY SUFFICIENT TO KEEP OLIVINE CRYSTALS AWAY FROM THE BASE OF THE FLOW. THIS GIVES RISE TO A PYROXENE-RICH, OLIVINE-DEFICIENT MARGIN.
CRYSTALLIZATION OF CLINOPYROXENE TO FORM PYROXENE-RICH MARGINAL ZONE
20
15
SCALE IN METRES
10
5
0
THE TRANSITION ZONE IS CONTINUOUSLY GRADATIONAL IN COMPOSITION BETWEEN THE INTRAFASCICULATE-TEXTURED GABBRO ABOVE AND THE OLIVINE CUMULATE ZONE BELOW. ROCKS OF THE TRANSITION ZONE CONSIST OF SUSPENDED OLIVINE AND SKELETAL CLINOPYROXENE CRYSTALS IN A MATRIX DOMINATED BY INTRAFASCICULATE-TEXTURED INTERGROWTHS BETWEEN CLINOPYROXENE AND PLAGIOCLASE.
THE FLOW TOP ZONE IS COMPOSED OF A FINE GRAINED, VESICULAR, CLINOPYROXENE SPINIFEX TEXTURED ROCK THAT GRADES DOWNWARD INTO INTRAFASCICULATE-TEXTURED GABBRO.
THE OLIVINE CUMULATE ZONE IS COMPOSED OF CUMULUS POLYHEDRAL OLIVINE SUSPENDED BY A MATRIX OF CLINOPYROXENE AND PLAGIOCLASE IN INTRAFASCICULATE-TEXTURED INTERGROWTH AND GLASS. FURTHER ACCUMULATION OF OLIVINE CRYSTALS WAS ARRESTED BY CRYSTALLIZATION AND QUENCHING OF INTERCUMULUS LIQUIDS.

FIGURE 18: Proposed origin of Fox River north 1 layered flow

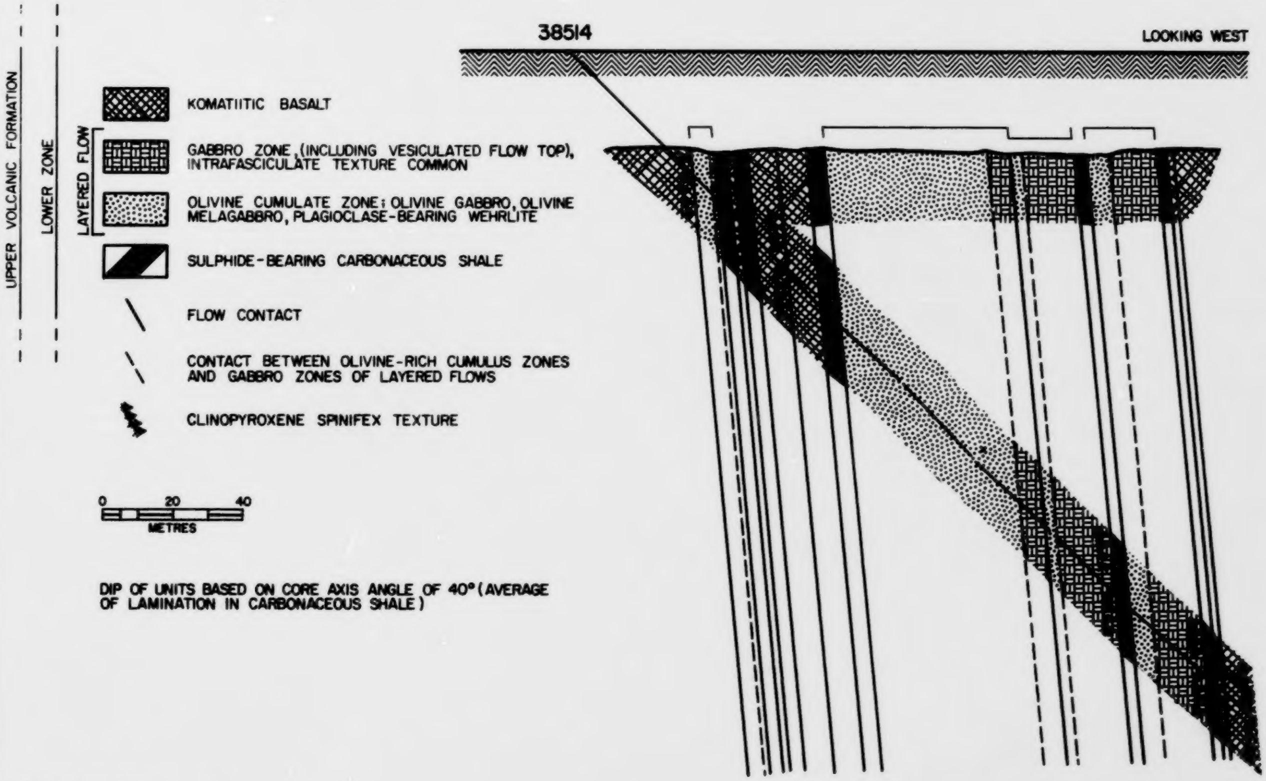

38514
LOOKING WEST
UPPER VOLCANIC FORMATION
LOWER ZONE
LAYERED FLOW
KOMATIITIC BASALT
GABBRO ZONE (INCLUDING VESICULATED FLOW TOP), INTRAFASCICULATE TEXTURE COMMON
OLIVINE CUMULATE ZONE: OLIVINE GABBRO, OLIVINE MELAGABBRO, PLAGIOCLASE-BEARING WEHRLITE
SULPHIDE-BEARING CARBONACEOUS SHALE
FLOW CONTACT
CONTACT BETWEEN OLIVINE-RICH CUMULUS ZONES AND GABBRO ZONES OF LAYERED FLOWS
CLINOPYROXENE SPINIFEX TEXTURE
0
20
40
METRES
DIP OF UNITS BASED ON CORE AXIS ANGLE OF 40° (AVERAGE OF LAMINATION IN CARBONACEOUS SHALE)

FIGURE 19: DDH 38514

Layered flows

Each of the four complete layered flows intersected consists of an olivine cumulate zone, overlain by a cumulus to complexly textured gabbro zone, that grades into a vesiculated flow top. The proportion of olivine cumulate rocks to gabbro (including flow top) is highly variable, ranging from 8:1 to 1:5. These layered flows are similar to the layered flow of Fox River north 1 in that they lack a clinopyroxenite horizon between the olivine cumulate and gabbro zones. Marginal zones are less well-developed in these flows, although the base of the largest flow is olivine deficient, and contains numerous clinopyroxene skeletal segments as a cumulus phase, along with completely recrystallized olivine and plagioclase (Plate 30).

Rocks of the olivine cumulate zones were initially composed of olivine and chromite as cumulus phases, and clinopyroxene and plagioclase as intercumulus minerals. The rocks were originally plagioclase-bearing wehrlite to olivine melagabbro in composition. Olivine occurred as polyhedral crystals with slightly rounded to sharp terminations, and ranged from 0.5 to 1.5 mm in long axis dimension. The crystals do not display any preferred orientation. Clinopyroxene is well-preserved, and occurs as large poikilitic plates (up to 1 cm), and as finer grained, discrete interstitial crystals. Plagioclase formed smaller poikilitic plates (up to 5 mm), and also occurred as dendritic to spherulitic crystals with splayed, divergent terminations. This latter variety has clinopyroxene occupying the originally hollow spaces and results in the characteristic complex texture. The ultramafic rocks have been substantially recrystallized with olivine being replaced by talc ± tremolite ± chlorite ± magnetite. Plagioclase has been replaced by a fine grained, in some cases nearly isotropic matte of chlorite. Fine grained sphene is commonly associated with the chlorite. Clinopyroxene shows only incipient alteration to tremolite, and is well-preserved, and as a result defines and gives emphasis to the primary texture. Pyrrhotite, pentlandite, ilmenite, magnetite and sphene are opaque minerals that have been identified.

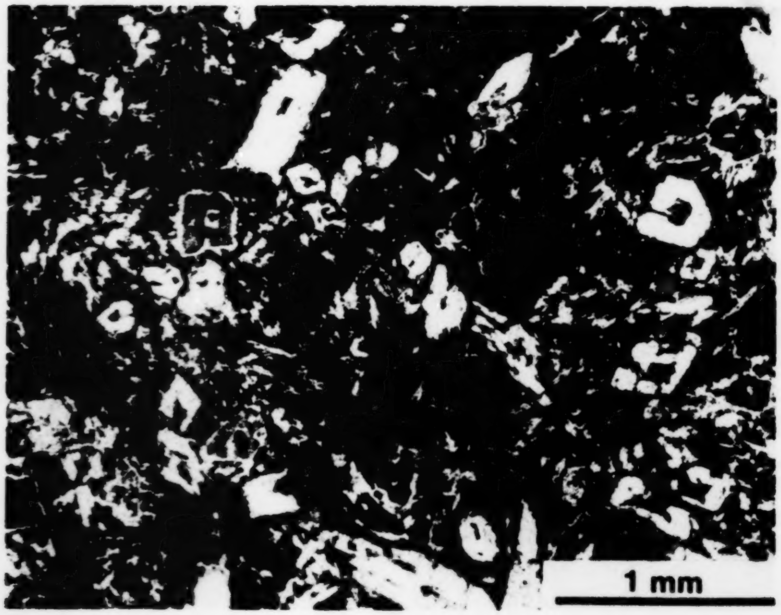


PLATE 30: Cumulus skeletal clinopyroxene segments. Rock originally composed of clinopyroxene and olivine. Plagioclase was a mincr constituent. Like most marginal zone rocks this rock has been substantially recrystallized. Note the incipient alteration of clinopyroxene to tremolite. Marginal zone, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-370) XN.

The rocks of the gabbro zones display a variety of compositions and textures, and rocks composed of cumulus clinopyroxene and plagioclase are rare. The rocks are characterized by elongate, blade-like, irregularly-shaped and skeletal clinopyroxene crystals in a matrix of fine grained, acicular to fibre-like plagioclase crystals (Plates 31, 32 and 33). The fine grained, acicular plagioclase crystals are commonly arranged in sheaf-like, partly radiating bundles that impart a strikingly unusual texture (Plate 34). In some examples, the apices of the sheaf-like bundles point in the same general direction, producing a preferred orientation, whereas in other rocks the sheaf-like bundles are randomly disposed. In a slightly coarser grained variety, clinopyroxene occupies the cores of elongate plagioclase crystals (Plate 35), a relationship referred to as intrafasciculate texture by Drever *et al.* (1972). Most clinopyroxenes are zoned, hour-glass and sector zones being developed. The elongate clinopyroxene crystals display sweeping extinction. In some rocks there are two distinct clinopyroxene varieties, early, subhedral to euhedral crystals characterized by hour-glass and sector zones, and later, dendritic-like crystals intergrown with spherulitic plagioclase. These unusual textural features indicate that the layered flows have a komatiitic character.

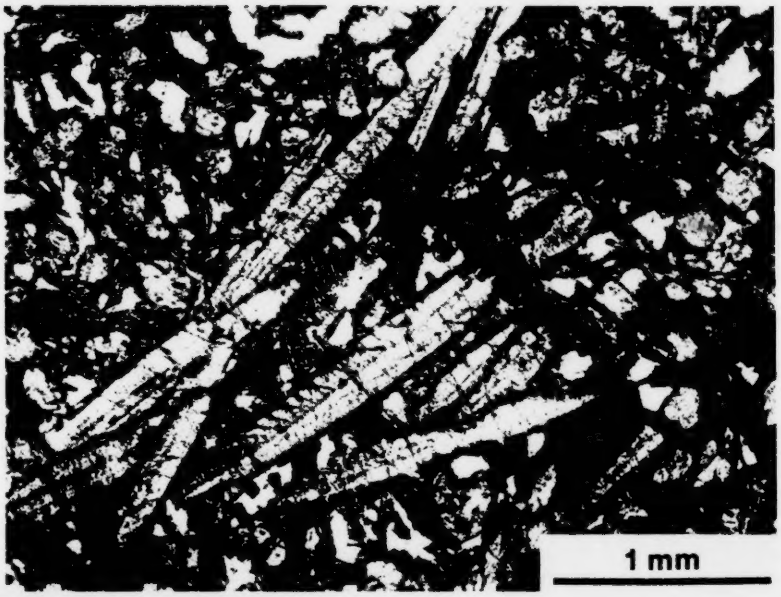


PLATE 31: Intersecting, blade-like clinopyroxene crystals. Fine grained, lath-like plagioclase crystals intergrown with fine grained clinopyroxene occupies the area between the clinopyroxene crystals. Highly irregular areas occupied by fine grained chlorite are miarolitic-like cavities or possibly deformed vesicles. Opaque mineral is graphite. Upper part, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-680) PL.

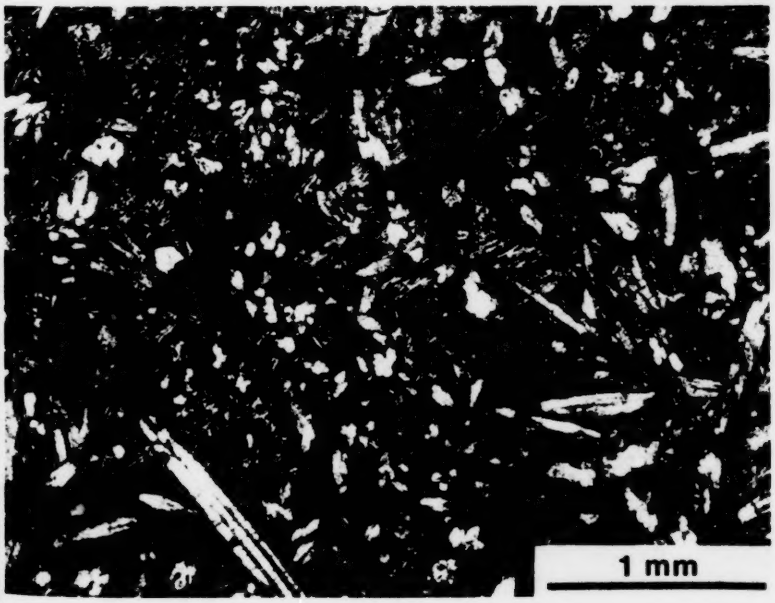
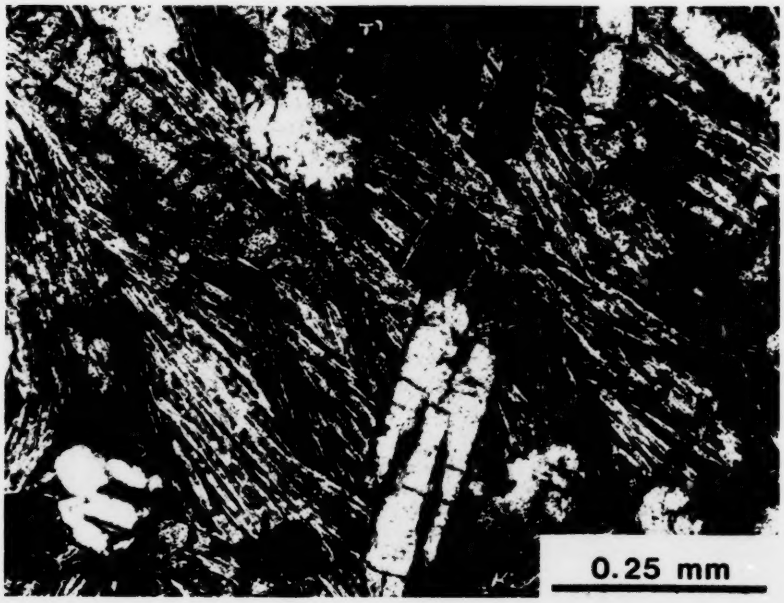


PLATE 32: Randomly oriented clinopyroxene skeletal segments and irregularly-shaped crystals in a groundmass composed of fine grained, lath-like to fibre-like plagioclase that forms groups of subparallel crystals. Each group has a different orientation than its neighbour. Upper part, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-820) XN.

PLATE 33: Detail of randomly oriented clinopyroxene skeletal segments and irregularly-shaped crystals, and groundmass composed of lath-like plagioclase crystals. Note groups of subparallel plagioclase crystals. Upper part, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-820) XN.



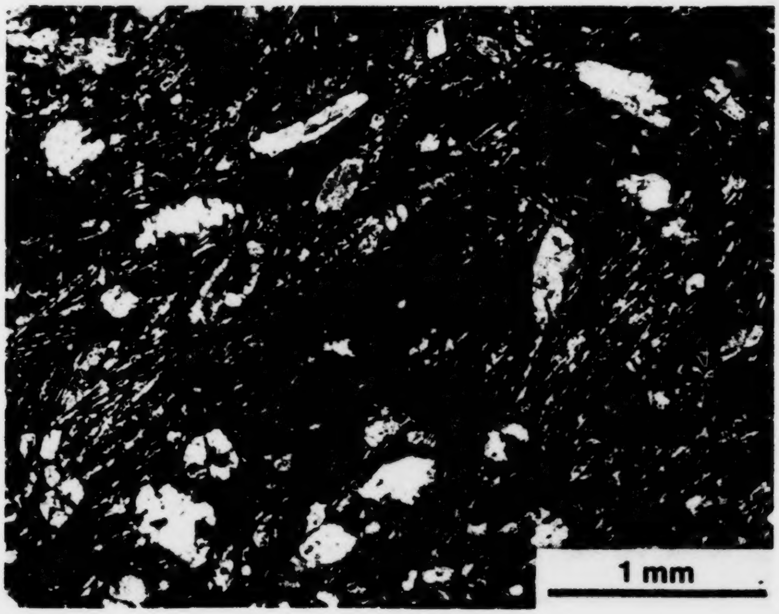
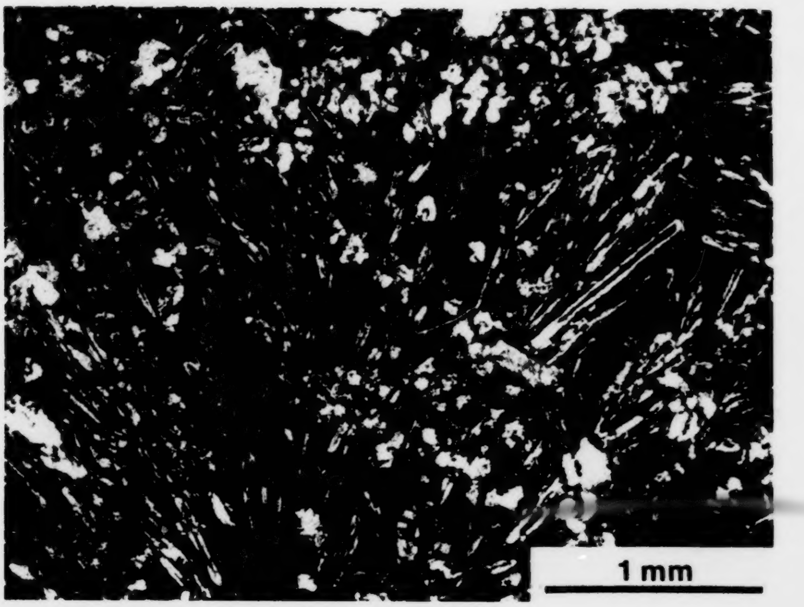


PLATE 34: Suspended, irregularly-shaped and stubby blade-like clinopyroxene crystals in groundmass distinguished by fine grained plagioclase as subparallel, partly radiating fan-like arrays. The apices of the individual fan-like arrays point in the same direction rendering a parallel-like arrangement to the groundmass plagioclase. Upper part, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-830) XN.

PLATE 35: Crudely equidimensional, irregularly-shaped clinopyroxene crystals in a groundmass of fine grained, lath-like to acicular plagioclase crystals that form fan-like, subradial crystal aggregates. Many of the plagioclase laths possess clinopyroxene cores and thus display a well-developed intrafasciculate texture. Upper part, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-700) XN.



A portion of the gabbro zone of the thickest layered flow is distinguished by branching, dendritic and spherulitic clinopyroxene crystals originally intergrown with plagioclase (Plates 36 and 37). An unusual rock, composed of randomly oriented plagioclase laths, many with a central core of clinopyroxene, in a groundmass characterized by a graphic-like intergrowth between clinopyroxene and plagioclase is associated with this zone (Plates 38 and 39). Curving and branching plagioclase laths associated with irregularly shaped clinopyroxene crystals (Plate 40) contribute to another unusually textured rock of the gabbro zone of another layered flow. These unusual textures indicate non-equilibrium crystallization conditions.

Irregularly-shaped areas occupied by fine grained, nearly isotropic chlorite ± quartz ± prehnite ± sulphide are a common feature of gabbro zone rocks (Plates 31 and 40). They are interstitial to the primary mineral assemblage, and this accounts for their irregular shape. They are similar to miarolitic cavities. The areas appear to represent original open spaces and are mineralogically indistinguishable from known vesicles. Similar features, in glass-bearing gabbro inclusions in hyaloclastites in Iceland, are considered to be deformed vesicles by Larsen (1979), who suggested that they formed in rocks, where the crystal framework was sufficiently rigid to resist the vesiculation process. There is a progression in gabbro zone rocks from these irregular areas or deformed vesicles near the base of the zone to spherical vesicles near the top. Deformed vesicles range from 0.2 mm to 1.5 mm, and spherical vesicles up to 3 mm have been observed. Tiny (0.01 mm), euhedral, semitranslucent, red-brown chromite crystals form clusters around vesicles in some flow top rocks.

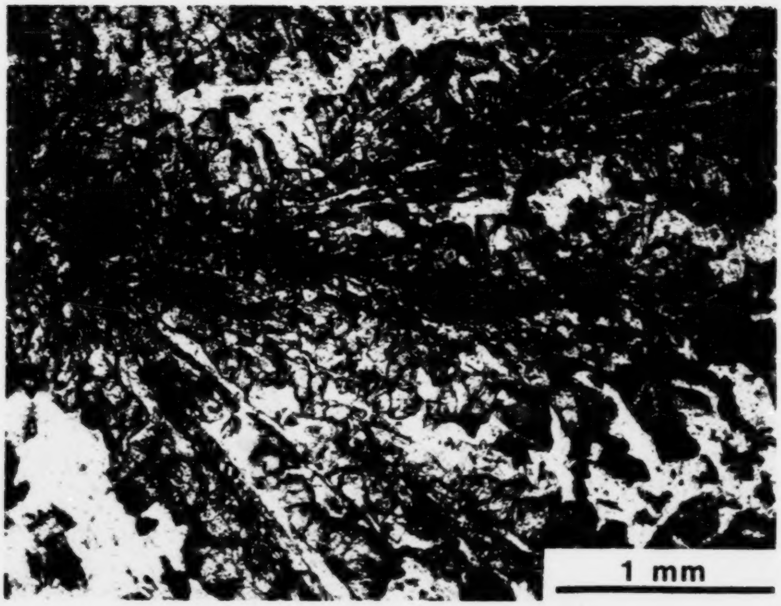


PLATE 36: Dendritic clinopyroxene crystals. Areas of low relief within and between crystals are occupied by a fine grained featureless matte of chlorite replacing plagioclase. Note how the dendritic crystals form a pattern of radially disposed plumes or branches emanating from a single point. Opaque mineral is sphene replacing ilmenite. Gabbro zone, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-630) PL.

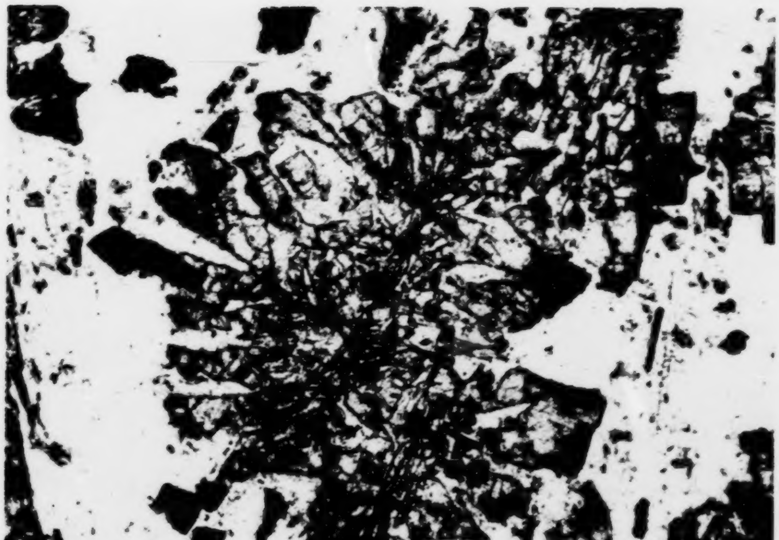
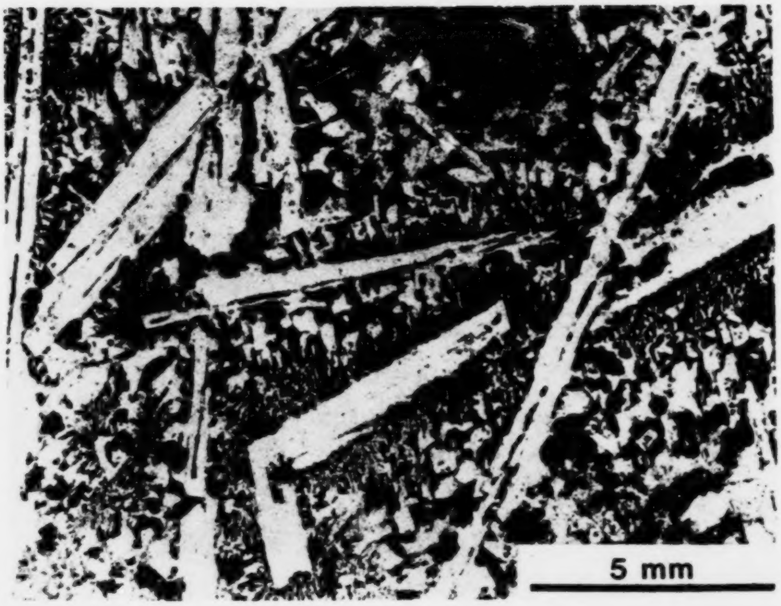


PLATE 37: Spherulitic clinopyroxene crystal. Areas of low relief are occupied by a very fine grained matte of chlorite replacing plagioclase. Opaque mineral is sphene replacing ilmenite. Gabbro zone, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-630) PL.

PLATE 38: Plagioclase laths pseudomorphously replaced by fine grained chlorite. Note partly continuous central pyroxene cores in some plagioclase crystals. Area between plagioclase crystals is distinguished by a graphic-like intergrowth between clinopyroxene and plagioclase. Gabbro zone, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-565) PL.



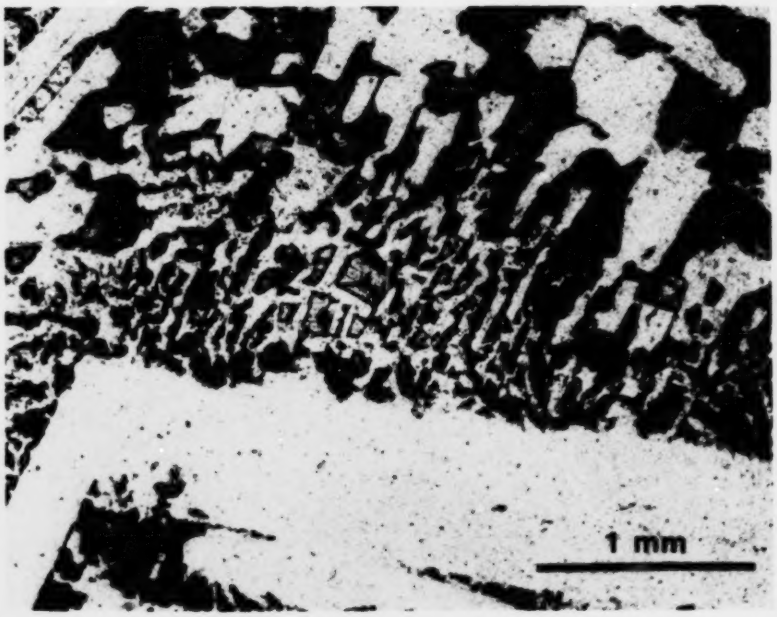
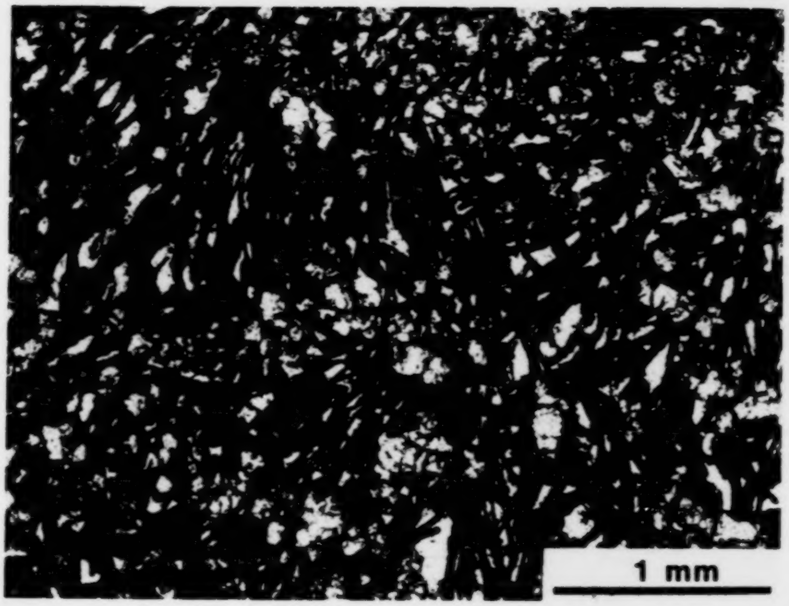


PLATE 39: Detail of plagioclase laths and graphic-like intergrowth seen in Plate 38 PL.

PLATE 40: Suspended, irregularly-shaped clinopyroxene crystals and elongate, lath-like, branching and curving plagioclase crystals. Many plagioclase crystals form subradial, fan-like arrays similar to the more densely packed groundmass arrays. Individual crystals are up to 2 mm long and groups of crystals are parallel over 4 mm. Irregularly-shaped, chlorite-filled areas are miarolitic-like cavities or possibly deformed vesicles. Plagioclase has been replaced by albite + chlorite + sphene + pumpellyite. Upper part, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-710) PL.

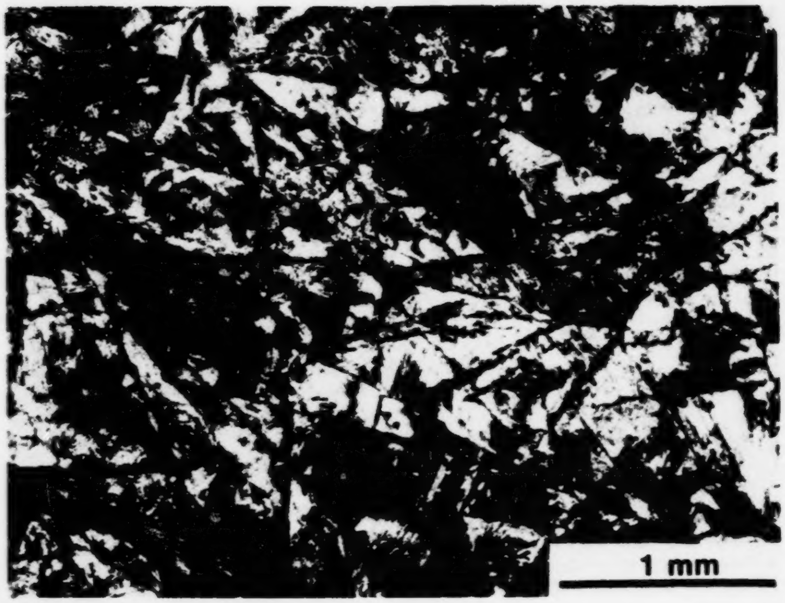


One layered flow is capped by delicate, plumose, frond-like and herringbone-like clinopyroxene, much of which is finely interwoven. The delicately developed clinopyroxene is subdivided into polygonal areas by randomly oriented, thin-laths (1-4 mm x 0.02 mm) of pseudomorphously replaced olivine (Plates 41 and 42). Some laths consist of joined skeletal olivine segments. Clusters of sharply terminated skeletal olivine, with hopper- or lantern-shapes, have been pseudomorphously replaced by quartz ± chlorite. The overall texture is visible megascopically, and closely approaches the classical olivine spinifex texture. Euhedral, fine grained, semitranslucent, red-brown chromite crystals, and fine grained sulphide grains are associated with the clusters of hopper-shaped olivines. Spherical vesicles are filled with chlorite and quartz.

Preserved primary minerals include clinopyroxene and chromite. Plagioclase has been pseudomorphously replaced by albite ± sphene ± muscovite ± pumpellyite ± quartz. Sphene pseudomorphously replaced original skeletal ilmenite. The preservation of clinopyroxene, and the pseudomorphous replacement of other primary minerals results in the primary rock textures being well-preserved. Prehnite and pumpellyite are distributed throughout gabbro zone rocks, whereas tremolite is extremely rare, and only occurs as fine grained spears associated with chlorite after olivine. This association of tremolite with olivine demonstrates the compositional control on the presence or absence of tremolite in these very low grade rocks. The layered flows originated in a manner similar to that described for the layered flow of Fox River north 1.

Pyrrhotite occurs as a sporadically distributed, fine grained interstitial phase, and has been identified in veinlets with quartz and prehnite. Graphite is fine grained and dust-like in character, and forms patch-like masses (up to 2 cm) in some gabbro zone rocks. It is likely derived during eruption of the lava onto unconsolidated carbonaceous shale, and subsequent incorporation of some of the shale into the lava.

PLATE 41: Randomly disposed, straight, plate-like olivine crystals in a fine grained, plumose, frond-like clinopyroxene groundmass. The olivine crystals which were originally ornamental chains have been replaced by chlorite and quartz. The olivine crystals divide the groundmass into numerous polygonal areas. Upper part, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-840) XN.



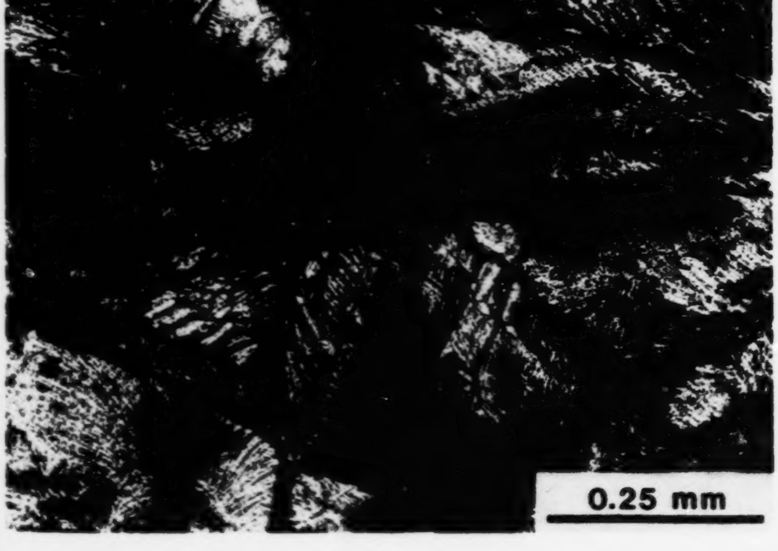


PLATE 42: Detail of polygonal areas displaying well-preserved plumose, frond-like clinopyroxene. Upper part, layered flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-840) XN.

KOMATIITIC BASALT FLOWS

Komatiitic basalt flows are identified on the basis of pyroxene spinifex, and by complex intergrowths between dendritic to spherulitic plagioclase and clinopyroxene. The flows tend to be simple, with gradational lithotextural changes, rather than sharp or dramatic changes as in the layered flows.

Several komatiitic basalt flows have flow top zones consisting of delicate, frond-like, plumose clinopyroxene that has been subdivided into polygonal areas by randomly oriented, elongate, olivine crystals up to 6 mm long (Plates 43 and 44). The olivine crystals have been pseudomorphously altered to chlorite ± quartz, and constitute up to 10 percent of the rocks. Hopper-shaped olivine crystals, also pseudomorphously replaced by serpentine, occur as discrete individuals, or as tight clusters of several crystals. Spherical vesicles are filled with chlorite ± carbonate. Euhedral, semitransluscent, red-brown chromite occurs as disseminated crystals. Pyrrhotite and pyrite occur as irregularly shaped grains associated with altered olivine crystals, and with filled vesicles in some rocks.

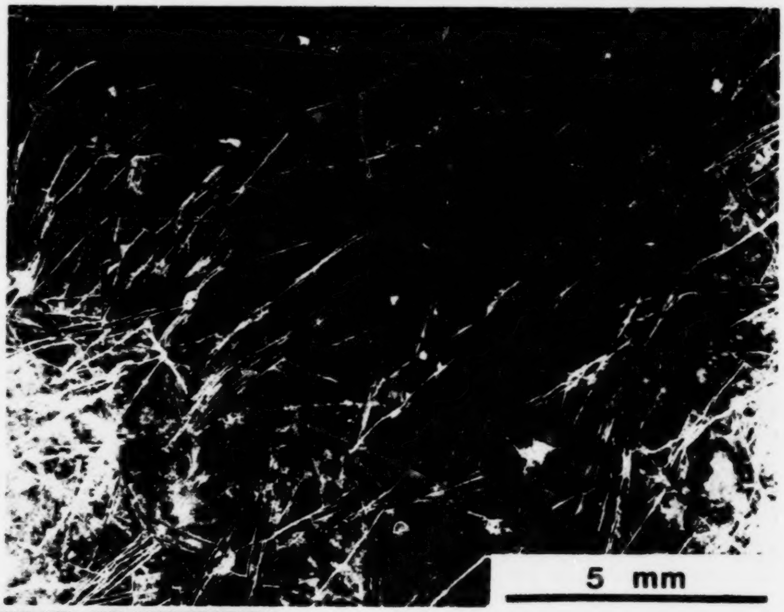


PLATE 43: Randomly disposed groups of parallel, plate-like olivine crystals. The crystal groups divide the groundmass into polygonal areas. The groundmass is composed of fine, delicate, plumose and frond-like clinopyroxene. The resulting texture resembles olivine spinifex. Olivine has been replaced by chlorite. Top of komatiitic basalt flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-908) PL.

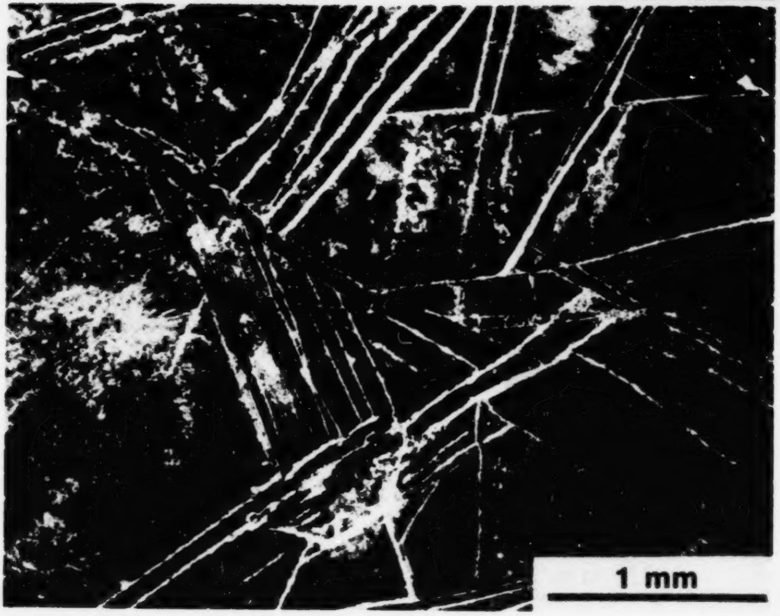


PLATE 44: Detail of olivine spinifex-like texture. Note groups of parallel, plate-like olivine crystals and outline of hopper olivine crystal. Top of komatiitic basalt flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-908) PL.

The resulting, megascopically visible texture approaches that of classical olivine spinifex, although olivine is not sufficiently abundant in the Fox River komatiitic flows for this term to be applied.

In the middle and lower parts of the flows, there are several types of intergrowth relationship between clinopyroxene and plagioclase. Clinopyroxene commonly occurs as elongate crystals parallel to (010) of plagioclase, and it also commonly occurs as continuous to partly discontinuous crystals with a distinctly dendritic pattern within individual plagioclase crystals. The most striking textural relationship is where clinopyroxene forms continuous to partly discontinuous crystals, displaying a 360° radial or rosette pattern within individual plagioclase crystals (Plate 45). In the latter example, the clinopyroxene seems to be emanating from a single point. All of these relationships are manifestations of the same intergrowth relationship, and the differences are due to original differences in plagioclase shape. The radial or rosette clinopyroxene patterns preserve original, almost perfectly spherulitic plagioclase crystals. The dendritic clinopyroxene patterns preserve original flattened plagioclase spherulites that develop elongate crystals with splayed, divergent terminations.

In one flow, there is a gradational progression downward from the olivine spinifex-like textured material into a rock characterized by 1 cm skeletal olivine crystals. The olivine crystals were originally constructed of joined skeletal segments, and have been pseudomorphously replaced by chlorite ± quartz ± tremolite. The randomly oriented olivine crystals dissect the rock into polygonal segments (Plates 46 and 47) which are distinguished by numerous, well-preserved skeletal clinopyroxene crystals. The clinopyroxenes range from straight and slightly curving crystals, made up of joined skeletal segments, to coarse frond-like or plumose crystals (Plates 48 and 49). The clinopyroxene crystals are set in a brownish nearly isotropic groundmass, that is interpreted to be an altered glass. Some pseudomorphously replaced hopper-shaped olivines, occur as sporadically distributed crystal clusters. Fine grained, euhedral chromite is a disseminated phase, and sulphide grains with ragged outlines are associated with some altered olivine crystals, and with filled vesicles. This rock phase is gradational into a well-developed clinopyroxene spinifex textured rock. The rock is distinguished by numerous sprays or divergent sheaves of elongate clinopyroxene crystals (Plate 50). Individual sprays are up to 1 cm long, and the clinopyroxene crystals occur in a groundmass composed of a nearly featureless matte of alteration products after original fine grained plagioclase. The alteration products are albite ± quartz ± muscovite ± sphene ± carbonate. The elongate clinopyroxene crystals have an irregular outline, and basal sections are partly skeletal in character. Many of the crystals have a medial line along the length of the crystal. Aggregates of euhedral chromite are randomly distributed as are quartz-filled, spherical vesicles.

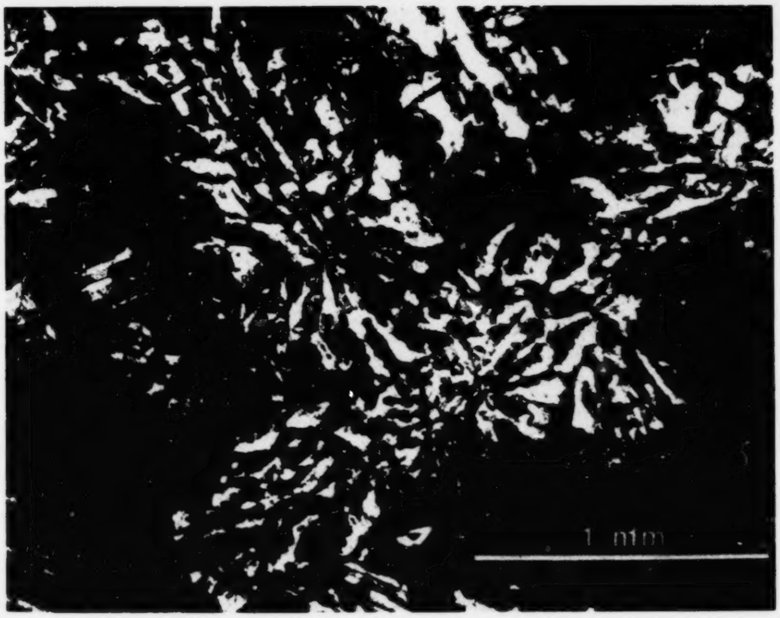


PLATE 45: Dendritic and spherulitic plagioclase and clinopyroxene crystals. Plagioclase forms continuous to partly continuous crystals. The original basic plagioclase has been replaced by albite. Dark areas are irregular, collapsed vesicles or miarolitic cavities. Komatiitic basalt flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-310) XN.

PLATE 46: *Etched slab displaying randomly disposed ornamental chain olivine crystals in a groundmass composed of ornamental chain clinopyroxene crystals, plumose, frond-like clinopyroxene and altered glass (see photomicrograph, Plate 47, for detail). Dark spots are polyhedral and hopper olivine crystals. Top of komatiitic basalt flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-900).*

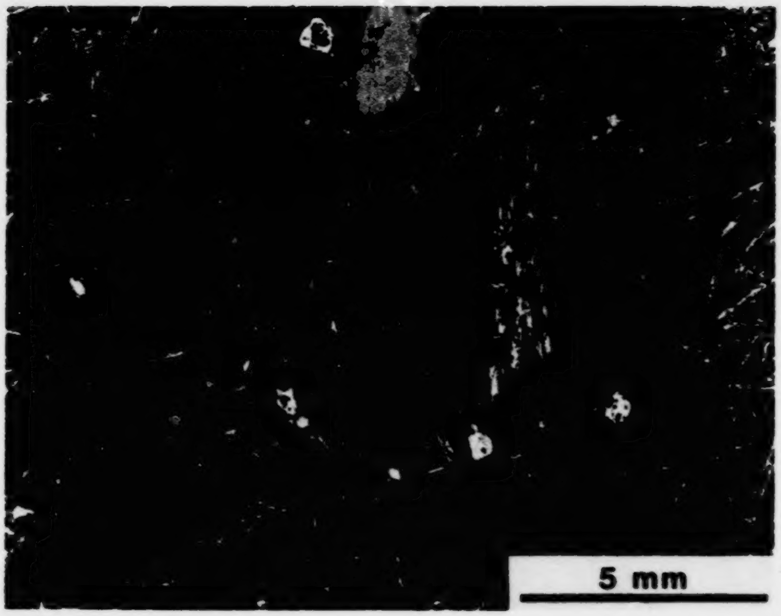
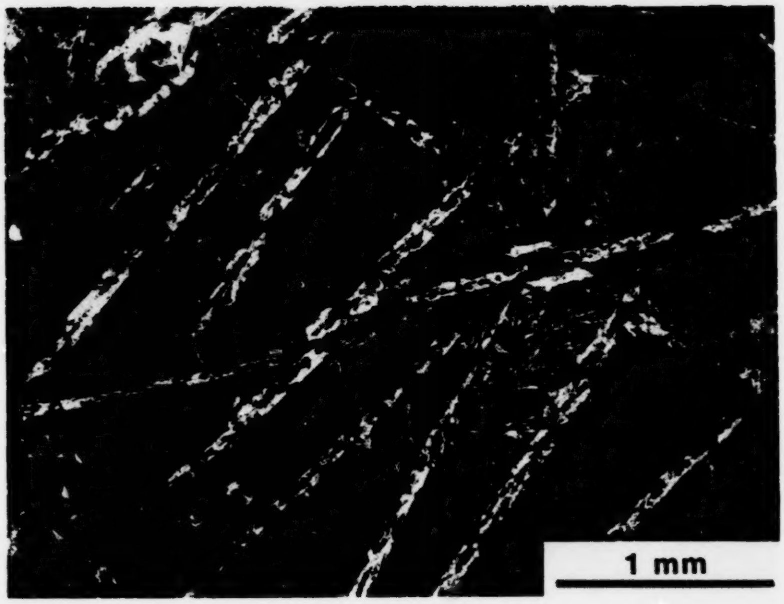


PLATE 47: *Randomly disposed, ornamental chain olivine crystals, up to 1 cm long, in a groundmass composed of ornamental chain clinopyroxene crystals, fine to coarse plumose, frond-like clinopyroxene and altered glass. Note aggregation of coarser, skeletal clinopyroxene crystals. Olivine has been replaced by chlorite ± quartz ± tremolite. Irregularly-shaped areas are vesicles filled with chlorite ± quartz ± magnetite ± pyrrhotite. Texture is similar to olivine spinifex. Top of komatiitic basalt flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-900) PL.*

PLATE 48: Detail of olivine spinifex-like texture. Note large ornamental chain olivine crystals, finer ornamental chain clinopyroxene crystals and frond-like clinopyroxene. Top of komatiitic basalt flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-900) PL.



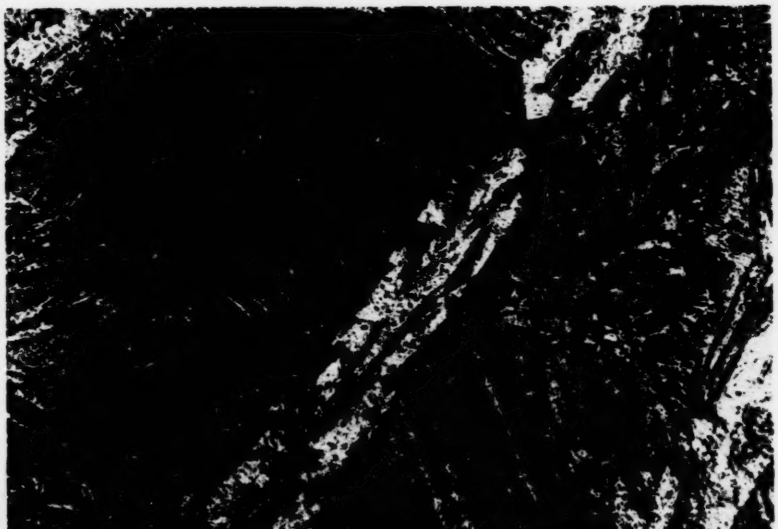
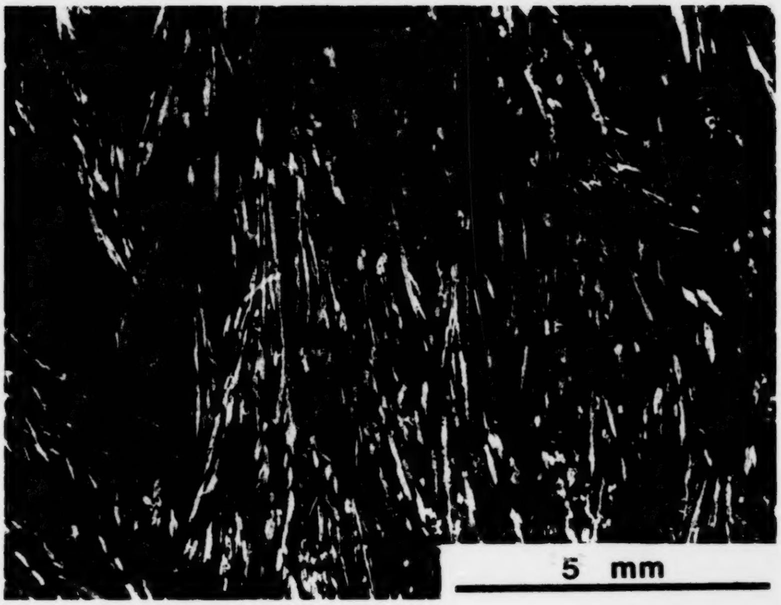


PLATE 49: Detail of ornamental chain olivine crystal, smaller ornamental chain clinopyroxene crystals, plumose frond-like clinopyroxene and featureless altered glass. Top of komatiitic basalt flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-900) PL.

PLATE 50: Elongate, slightly curving clinopyroxene blades, forming subparallel, divergent sheaves up to 1 cm long. The resulting texture is clinopyroxene spinifex. Smaller clinopyroxene crystals are irregular in shape and some are skeletal in character. The groundmass was originally composed of fine grained plagioclase laths, some occurring as subparallel crystal groups, and some in fan-like arrays. The rock was originally highly vesicular. Top of komatiitic basalt flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-890) XN.



Well-developed pyroxene spinifex textured rock grades into the basal part of the flow that is characterized by partly settled, highly skeletal clinopyroxene in a groundmass of highly altered, spherulitic plagioclase intergrown with clinopyroxene. Thus, there is strong indication of two clinopyroxenes, an early, settled clinopyroxene, and a later groundmass clinopyroxene. In the upper part of one komatiitic flow, elongate, segmented clinopyroxene crystals (Plate 51) composed of individual segments that are not in perfect optical continuity, give rise to anomalous, sweeping extinction (Plate 52). The spherulitic plagioclase has been replaced by albite ± chlorite ± quartz ± muscovite ± sphene. Euhedral, hopper olivine crystals have been replaced by chlorite, quartz and carbonate. Deformed vesicles are filled with chlorite ± quartz ± prehnite ± carbonate.

The komatiitic flows have originated through extrusion of nearly crystal-free lava. Only very fine chromite crystals, and possibly some sulphide minerals were carried in suspension during extrusion. Olivine crystallized first followed by clinopyroxene. In both cases rapid crystallization caused a departure from equilibrium crystal growth, and the consequent development of skeletal crystals. This is most dramatic in flow top zones where spinifex textures were generated. Olivine, although present, is not abundant, and cumulus olivine crystals in the lower part of the flows are rare. Settling of skeletal clinopyroxene crystals toward the base of flows was arrested by the final crystallization, which gave rise to spherulitic plagioclase and intergrown clinopyroxene. The unusual crystal habits of the major silicate minerals indicates that non-equilibrium crystallization conditions were maintained from the beginning to the end of crystallization. The frond-like, plumose clinopyroxene, ornamental chain-like clinopyroxene and olivine, and the dendritic and spherulitic plagioclase crystals represent crystallization under high cooling rates, and high degrees of supercooling (Lofgren, 1979).

The bulk mineralogical composition of the komatiitic basalt flows is estimated to have been gabbroic, and consequently the lava is considered to have been gabbroic in composition upon extrusion.

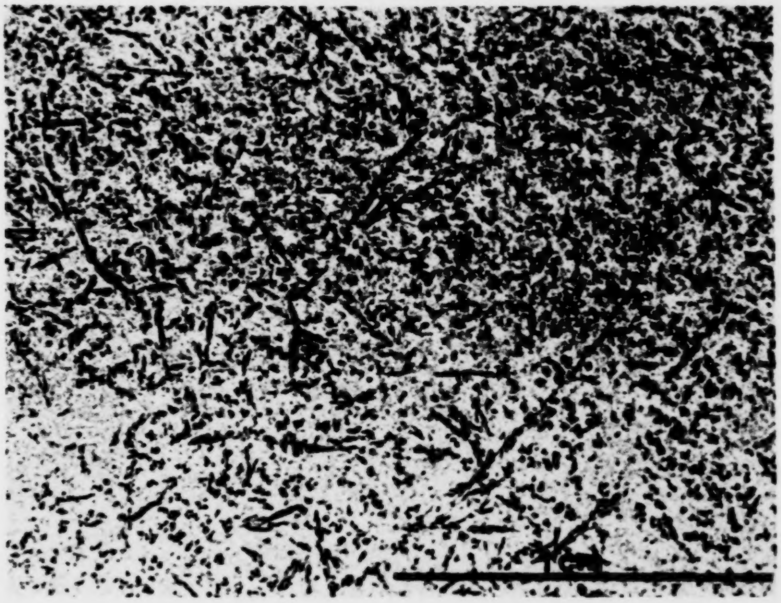


PLATE 51: Etched slab displaying randomly oriented skeletal clinopyroxene crystals. Many clinopyroxene crystals have irregular shapes and display hollow cores. The groundmass is distinguished by dendritic and spherulitic clinopyroxene intergrown with plagioclase (see photomicrograph, Plate 52, for detail). Upper part, komatiitic basalt flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-870).

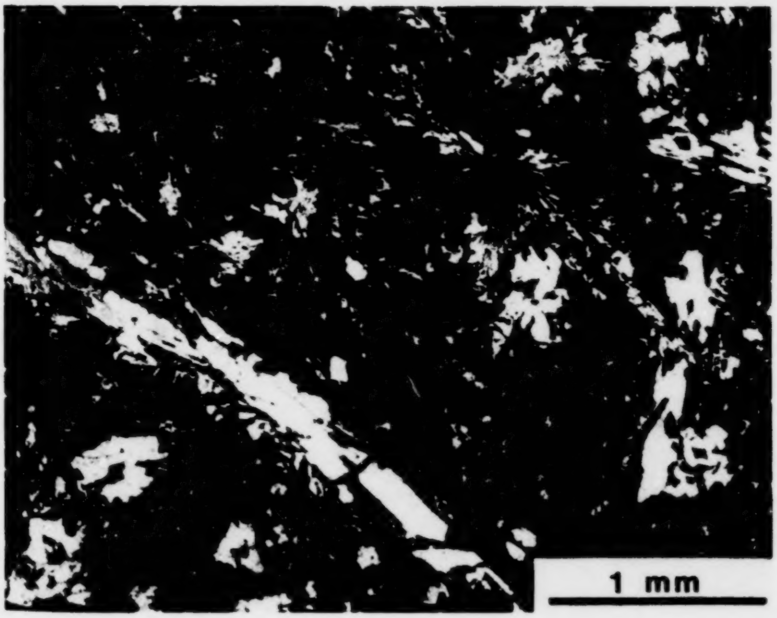


PLATE 52: Elongate, segmented clinopyroxene crystal formed by elongate crystal segments. Each segment is not in perfect optical continuity with its neighbour giving rise to anomalous sweeping extinction. Smaller clinopyroxene crystals possess highly irregular shape and many display hollow cores. The groundmass is distinguished by dendritic and spherulitic clinopyroxene intergrown with plagioclase. The rock was originally vesicular. Upper part komatiitic basalt flow, Lower zone, Upper volcanic formation, DDH 38514 (38514-870) XN.

OTTER FALLS SECTION, STUPART RIVER

A series of pillowed olivine clinopyroxenites, interrupted by a sequence of layered flows, is exposed in the Otter Falls section of the Stupart River (Fig. 20). The pillowed flow series south of the layered flows is exposed over a distance of 90 m in discontinuous outcrop, and that north or stratigraphically above the layered flows is exposed over a distance of 20 m.

The pillows range from sub-spherical masses 40 cm in diameter, to elliptical masses measuring 2 x 1 m, and there appears to be no size organization to their distribution (Plate 53). The pillows are very tightly packed and molded to each other, and consequently there is little interpillow space. Vesicles are absent, and pillow rims seldom exceed 2 cm. Internal cavities are rare, a few small single cavities being observed. Three narrow (<1.5 m wide), massive, columnar jointed flows are intercalated with the pillowed series south of the layered flows. They occur over the upper 20 m of the series, and the uppermost massive flow overlies a 2 m zone of pillow breccia.

PLATE 53: Pillowed olivine clinopyroxenite. Note range in size of individual pillows, tight packing, narrow rims and lack of cavities and vesicles. Vertical tape, which is 14 cm long, indicates direction of bedding. Horizontal tape indicates direction of dip. Tops are to the left. Middle zone, Upper volcanic formation, Otter Falls section, Stupart River.

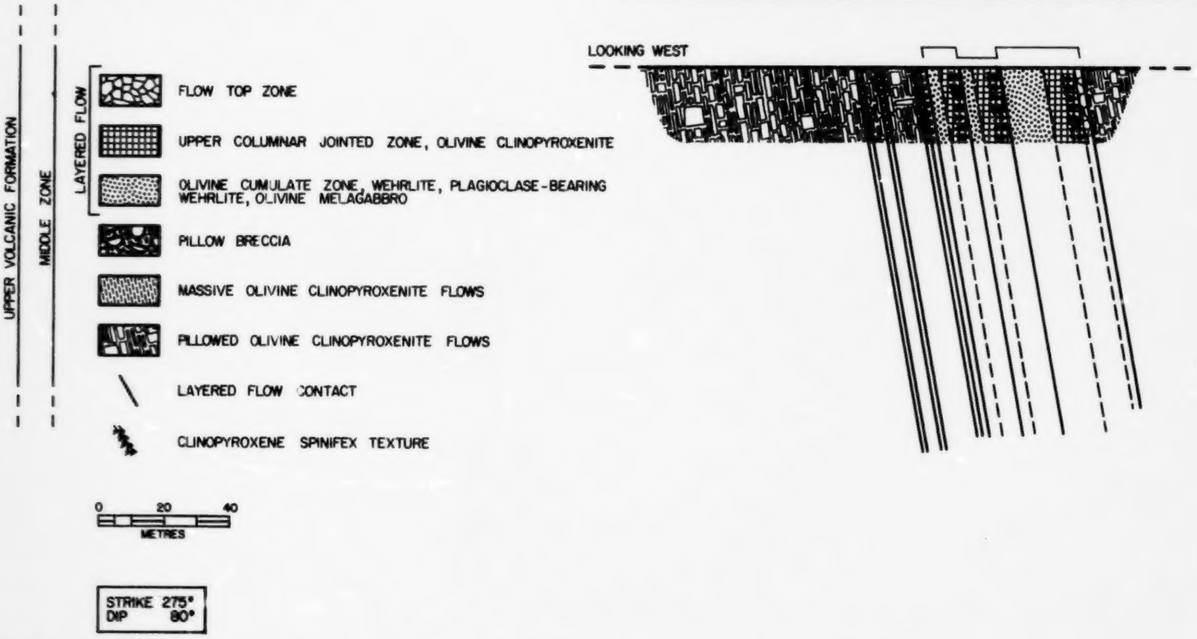

LOOKING WEST
UPPER VOLCANIC FORMATION
MIDDLE ZONE
LAYERED FLOW
FLOW TOP ZONE
UPPER COLUMNAR JOINTED ZONE, OLIVINE CLINOPYROXENITE
OLIVINE CUMULATE ZONE, WEHRLITE, PLAGIOCLASE-BEARING WEHRLITE, OLIVINE MELAGABBRO
PILLOW BRECCIA
MASSIVE OLIVINE CLINOPYROXENITE FLOWS
PILLOWED OLIVINE CLINOPYROXENITE FLOWS
LAYERED FLOW CONTACT
CLINOPYROXENE SPINIFEX TEXTURE
0
20
40
METRES
STRIKE 275°
DIP 80°

FIGURE 20: Otter Falls section, Stupart River

The pillowed olivine clinopyroxenites are characterized by aggregates of pseudomorphously replaced hopper- and lantern-shaped olivine crystals, and ornamental chain-like, skeletal olivine crystals up to 1.5 mm long, in a fine grained groundmass, typified by delicate frond-like, plumose and herringbone clinopyroxene (Plates 54 and 55). The olivine content ranges up to 30 percent. Disseminated, euhedral, red-brown chromite crystals are common, and illustrate the ultramafic character of the rocks. Olivine has been replaced by chlorite ± quartz ± tremolite, and irregularly shaped, ragged sulphide grains are associated with the altered olivine. A slight variation in grain size of the groundmass clinopyroxene, and in olivine content are the only variations noted. The pillowed flows overlying the layered flow sequence are identical in form and composition to the underlying pillowed series.

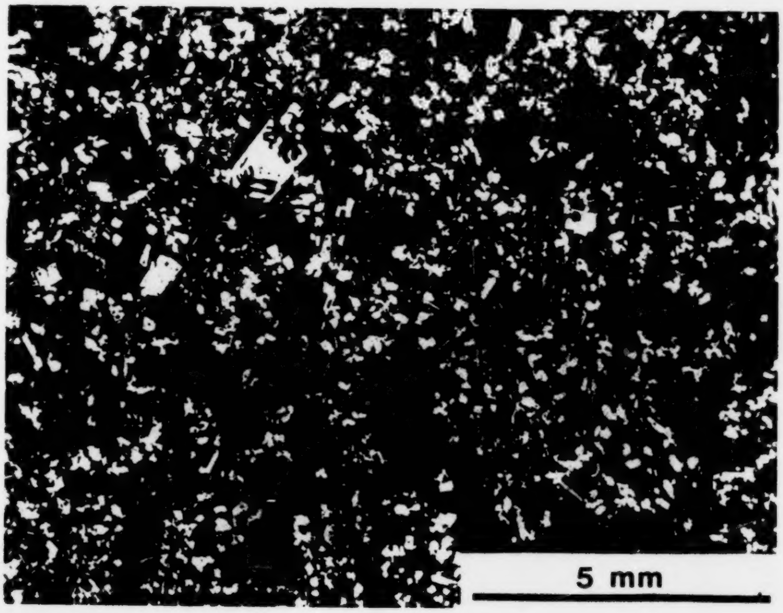


PLATE 54: Polyhedral and hopper olivine crystals in a plumose, frond-like clinopyroxene groundmass. Olivine has been pseudomorphously replaced by chlorite ± tremolite ± quartz. Pillowed olivine clinopyroxenite, Middle zone, Upper volcanic formation, Otter Falls section, Stupart River (03-76-88-1) PL.

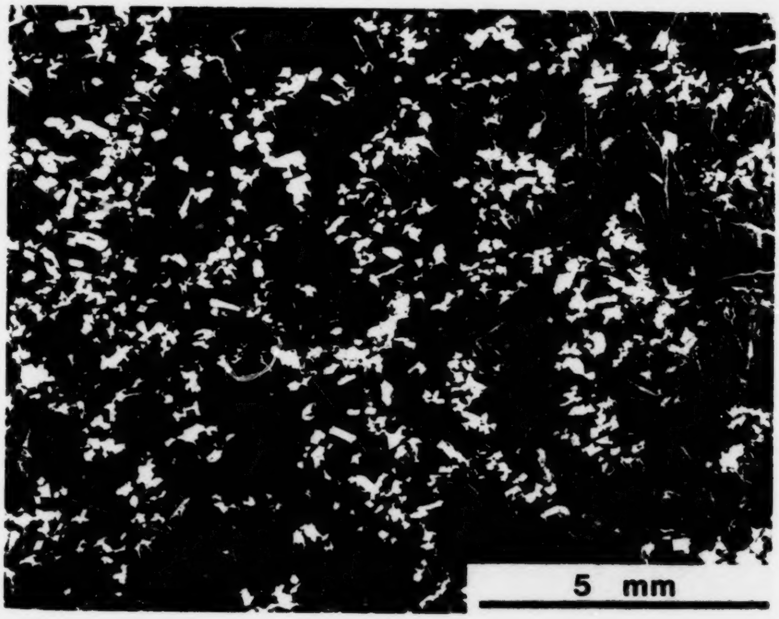


PLATE 55: Polyhedral, hopper and ornamental chain olivine crystals in plumose, frond-like and herringbone-like clinopyroxene groundmass. Olivine has been pseudomorphously replaced by chlorite + tremolite + quartz. Pillowed olivine clinopyroxenite, Middle zone, Upper volcanic formation, Otter Falls section, Stupart River (03-75-77-2) PL.

The layered flow (composite flow, Scoates, 1977) sequence comprises three flows, ranging from 10 to 25 m thick, each of which is composed of a lower, olivine cumulate zone, and an upper, columnar jointed zone (Plate 56). The olivine cumulate zones form smooth, dark reddish-brown outcrops, with widely spaced joints giving rise to an open rectangular pattern. This is in marked contrast with the upper zone which is characterized by somewhat irregular, straight to curving columns formed by numerous, closely spaced joints (Plate 57). The columns are oriented approximately at right angles to the direction of strike of the flow, and they tend to become increasingly curvilinear toward the top of the flow. Near the top of the flow, the columns commonly display a well-developed fan-like arrangement (Plate 58). The rocks of the upper zone are light grey, and contrast with the dark reddish-brown, lower zone rocks. The uppermost parts of the upper zones are marked by 10 to 20 cm thick, dark grey to black, rubbly breccia zones. Despite the presence of a breccia zone, the nature of the outcrop makes placement of flow contacts very difficult (Plate 59). The contact between lower and upper zones within flows is gradational over several centimetres. At a distance this contact appears to be sharp because of the dramatic change in the nature of the jointing pattern and the colour contrast of the rocks, as previously noted.

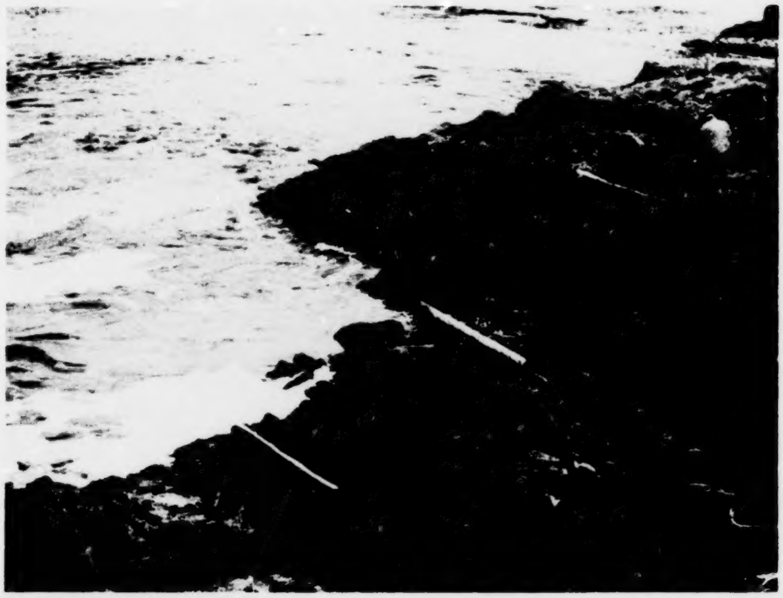


PLATE 56: Lowermost layered flow, layered flow sequence, Otter Falls section, Stupart River. The olivine cumulate zone forms the massive blocky jointed part of the outcrop between the bottom and middle logs. The upper, columnar jointed zone occurs between the middle and upper logs. Figure at upper right is seated on the olivine cumulate zone of next overlying flow. Tops are to the upper right. Middle zone, Upper volcanic formation.

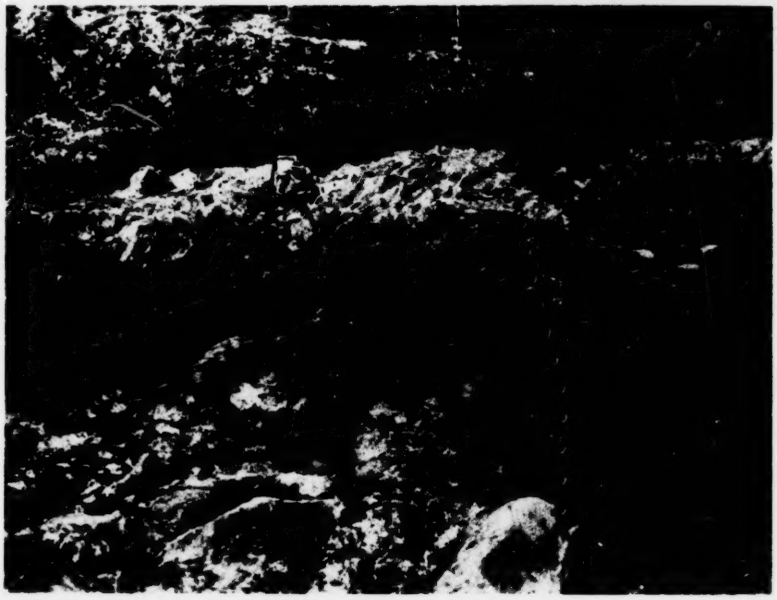


PLATE 57: Middle layered flow, layered flow sequence, Otter Falls section, Stupart River. Blocky, rectangular jointed rock in foreground is olivine cumulate zone. Upper columnar jointed zone of the same flow is in the background. Haversack in centre-left background for scale. Middle zone, Upper volcanic formation.

PLATE 58: Detail of upper columnar jointed zone, seen in Plate 57. Note curvilinear nature of joints. White is quartz-carbonate filling cavity. Hammer handle is 35 cm long. Middle zone, Upper volcanic formation.

PLATE 59: Contact between lower and middle layered flows, layered flow sequence, Otter Falls section, Stupart River. Hammer handle is on fine grained, brecciated flow top. Hammer head rests on olivine cumulate zone of overlying flow. Hammer handle is 35 cm long. Middle zone, Upper volcanic formation.

The lower zone of each flow consists of cumulus polyhedral and skeletal olivine ± cumulus skeletal clinopyroxene, in a groundmass of coarse clinopyroxene plumes ± clinopyroxene, as skeletal crystal segments, and ornamental chain-like crystals ± altered glass (Plate 60). Olivine is not densely packed, indicating that its accumulation toward the flow base was not completely accomplished. In the middle flow, the olivines occur in a groundmass originally composed of dendritic plagioclase crystals with intergrown clinopyroxene. The uppermost flow has a cumulus phase composed of olivine and skeletal clinopyroxene in a groundmass of dendritic plagioclase and clinopyroxene. The two phases of clinopyroxene noted in other flows are also noted in these flows. Clusters of euhedral chromite crystals form a cumulus phase, and ragged disseminated sulphide is associated with the altered olivines. Chlorite ± tremolite ± talc pseudomorphously replace olivine, and chlorite ± sphene ± tremolite replaces plagioclase. Clinopyroxene is unaltered, or displays incipient alteration to tremolite.

The upper, columnar jointed zones are characterized by aggregates of hopper-, and lantern-shaped olivine crystals ± elongate, ornamental chain-like olivine crystals ± ornamental chain clinopyroxene crystals in a groundmass of fine, frond-like, plumose clinopyroxene (Plates 61, 62 and 63). These textures are visible megascopically (Plate 64). Many of these rocks are mineralogically and texturally indistinguishable from the pillowed olivine clinopyroxenites previously described. In the middle flow, the lower part of the columnar jointed zone is distinguished by numerous, skeletal clinopyroxene segments occurring as randomly distributed elements, and as groups of individuals, forming straight and curving, spiral, chevron and ornamental, chain-like crystals (Plates 65, 66 and 67). The fine grained, skeletal clinopyroxenes are in a brownish, nearly isotropic matrix interpreted to be altered glass. There is a progressive increase in the abundance of hopper-shaped olivine, as well as a progressive change from skeletal crystals to frond-like, plumose clinopyroxene, toward the top of this flow. The uppermost part of the flow contains hopper olivine and ornamental chain-like olivine crystals in a plumose clinopyroxene groundmass. The columnar jointed zone of the uppermost flow contains hopper olivine clusters in a groundmass of 4 to 6 mm long, ornamental chain-like clinopyroxene, and plumose clinopyroxene in brownish, nearly isotropic altered glass. The elongate clinopyroxene crystals are megascopically visible, and the rock is considered to possess pyroxene spinifex texture.

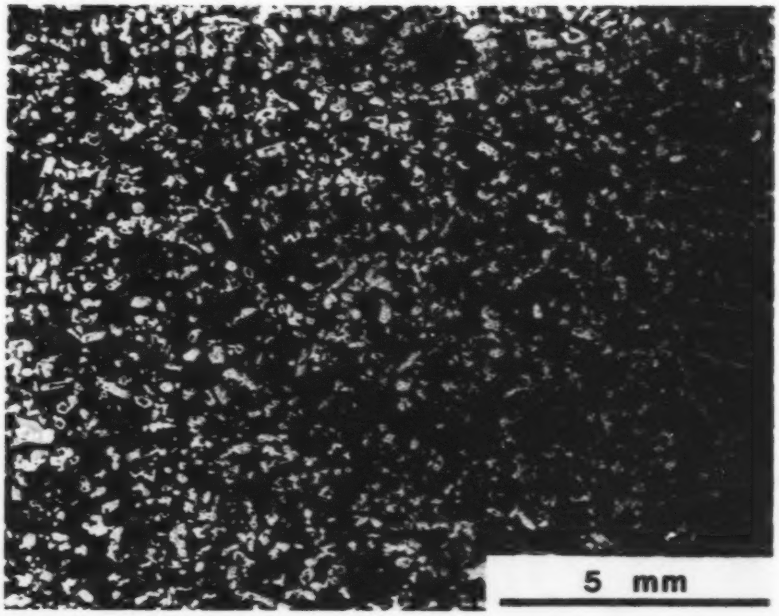
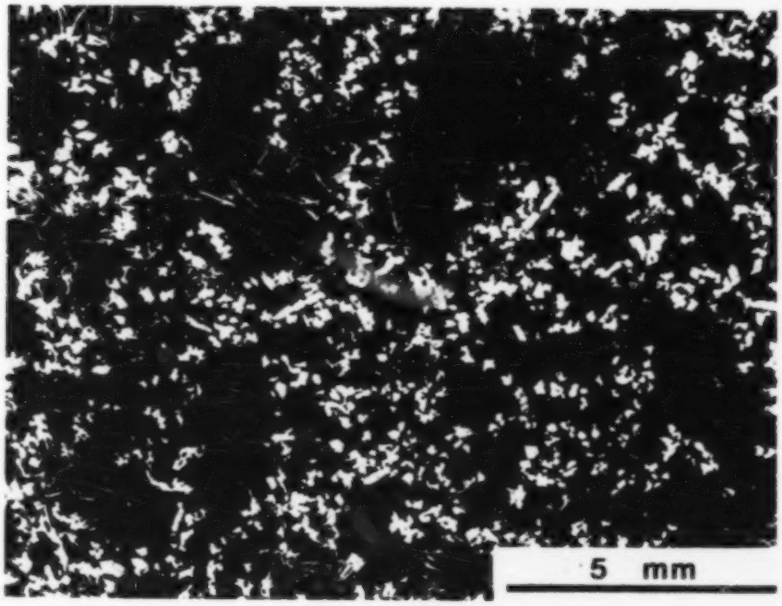


PLATE 60: Partly cumulus (suspended) euhedral, partly skeletal olivine crystals in a groundmass composed of skeletal and ornamental chain clinopyroxene crystals and altered glass. Opaque minerals are magnetite and pyrrhotite. Olivine has been pseudomorphously replaced by chlorite ± tremolite. Olivine cumulate zone, layered flow, Middle zone, Upper volcanic formation, Otter Falls section, Stupart River (03-76-92-1) PL.

PLATE 61: Suspended polyhedral, hopper and ornamental chain olivine crystals in a plumose, frond-like clinopyroxene groundmass. Olivine has been replaced by chlorite ± tremolite. Upper columnar jointed part, layered flow. Middle zone, Upper volcanic formation, Otter Falls section, Stupart River (03-75-92-4) PL.



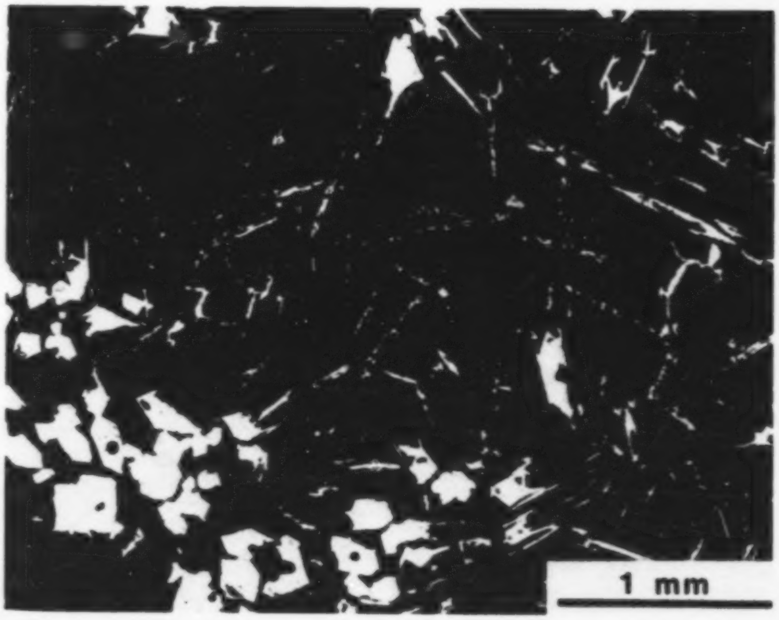
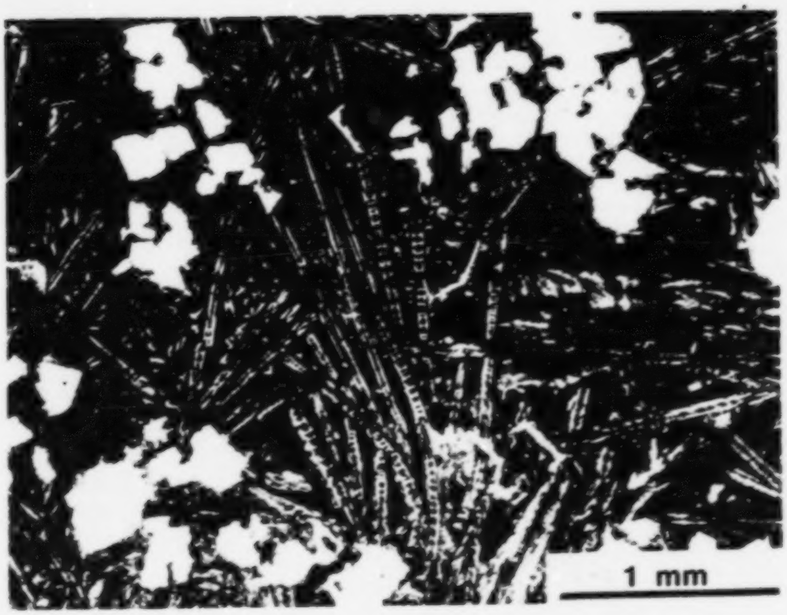


PLATE 62: Clusters of polyhedral, hopper and ornamental chain olivine crystals in a groundmass of plumose, frond-like clinopyroxene. Olivine has been pseudomorphously replaced by a fine grained matte of chlorite. Upper columnar jointed part, layered flow. Middle zone, Upper volcanic formation, Otter Falls section, Stupart River (03-76-92-5) PL.

PLATE 63: Clusters of polyhedral and hopper olivine crystals and randomly oriented ornamental chain clinopyroxene crystals in a groundmass composed of plumose, frond-like clinopyroxene and altered glass. The ornamental chain crystals are composed of joined skeletal segments. Upper columnar jointed zone, layered flow, Middle zone, Upper volcanic formation, Otter Falls section, Stupart River (03-75-77-3) PL.



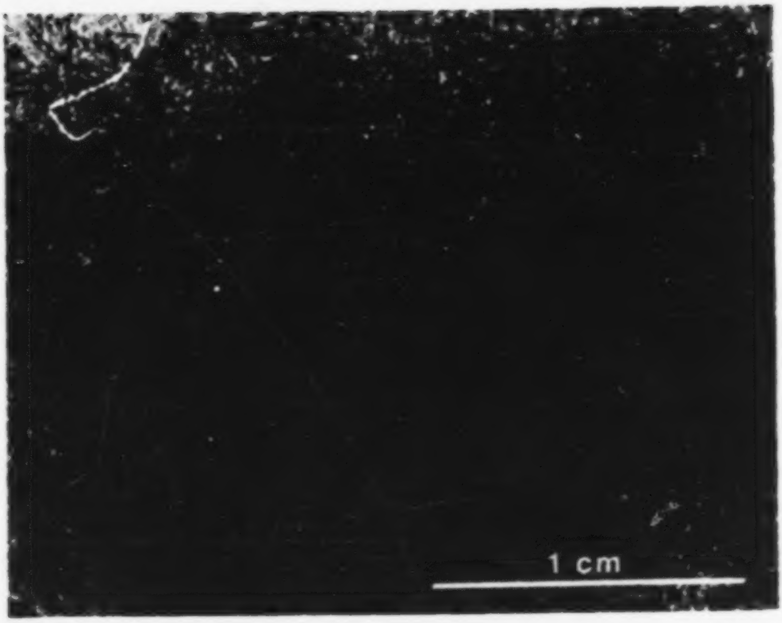


PLATE 64: Etched slab displaying randomly oriented ornamental chain clinopyroxene crystals and clusters of polyhedral and hopper olivine crystals in altered glass. Upper columnar jointed part, layered flow, Middle zone, Upper volcanic formation, Otter Falls section, Stupart River (03-75-77-9).

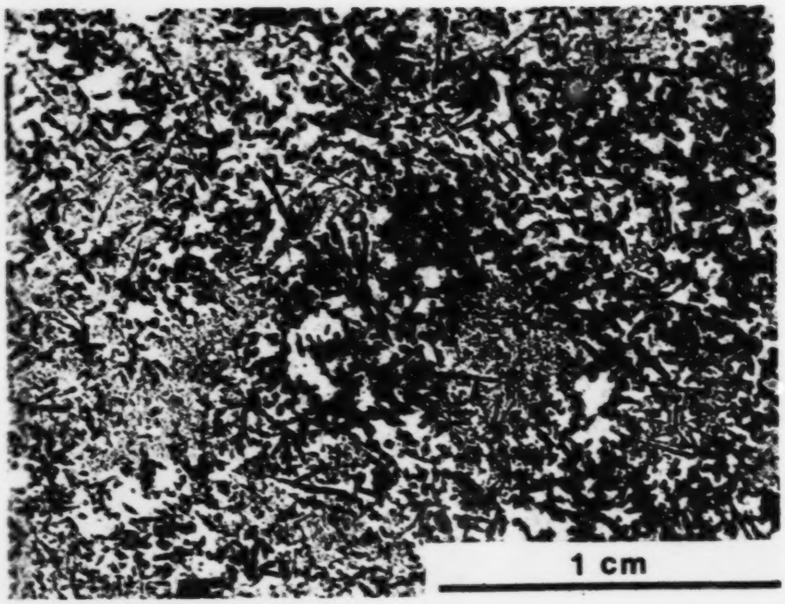


PLATE 65: Etched slab displaying randomly oriented clinopyroxene blades and finer grained clinopyroxene crystals displaying chevron kink habit in altered glass (see photomicrograph, Plate 66, for detail). Upper columnar jointed part, layered flow, Middle zone, Upper volcanic formation, Otter Falls section, Stupart River (03-76-92-8).

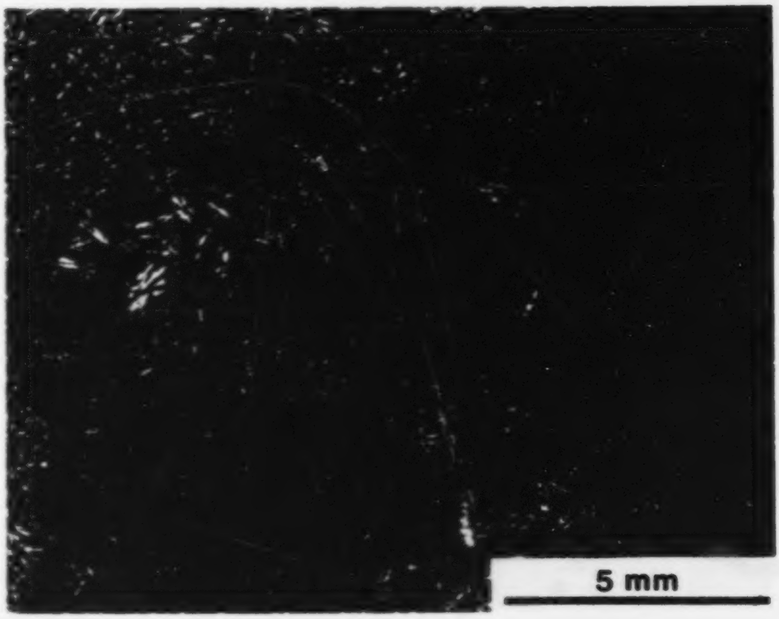
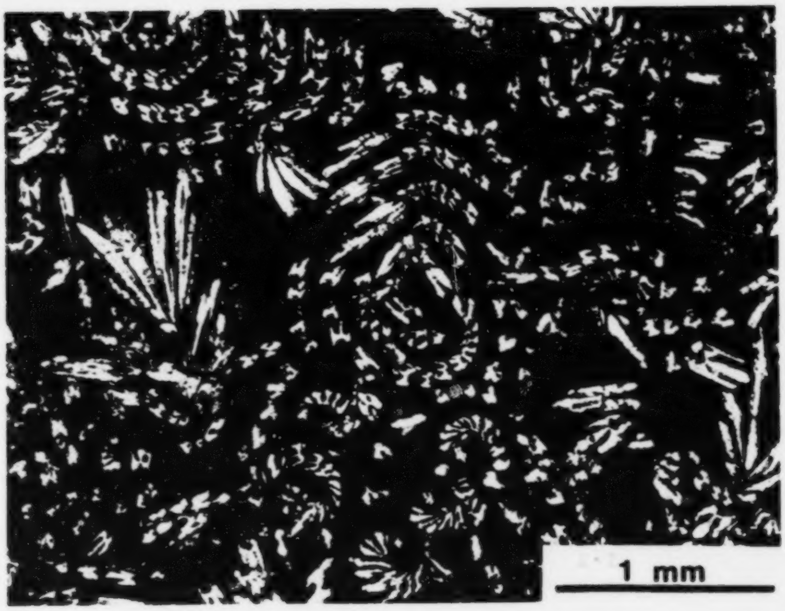


PLATE 66: M-, and bat wing-shaped skeletal clinopyroxene segments. Many segments are arranged to form disconnected, curving, bent and spiral skeletal crystals. The groundmass is altered glass. Upper columnar jointed part, layered flow, Middle zone, Upper volcanic formation, Otter Falls section, Stupart River (03-76-92-8) PL.

PLATE 67: Detail of M -, and bat wing-shaped skeletal clinopyroxene segments seen in Plate 66. PL.



The layered flows originated through extrusion of lava of clinopyroxenitic to olivine clinopyroxenitic composition. The minor amount of plagioclase in the rocks indicates that the normative plagioclase content of the lava was much lower than that of previously described layered flows. The presence of skeletal, hopper-shaped, and ornamental chain-like olivine crystals in the upper part of the flow (Plates 68 and 69) indicates that olivine was capable of crystallizing from the lava. It was previously noted that the extent to which olivine was a suspended phase prior to extrusion, versus its possible crystallization after extrusion was not known. However, the cumulus olivine-rich zones of the Otter Falls layered flows contain many skeletal olivine crystals indicating that some, and possibly all, of the olivine crystallized after eruption. As the flow rate slowed, olivine settled toward the base of the flow. Rapid crystallization under high rates of cooling is considered to be responsible for the hopper olivine-bearing, plumose clinopyroxenites of the upper zones. The spectacular rock containing numerous clinopyroxene segments in glass appears to represent incipient nucleation of clinopyroxene from numerous nucleation sites, followed immediately by quenching, and the consequent preservation of this unusual rock. The settling and accumulation of olivine was arrested, so that it became a suspended phase in a groundmass that represents rapid crystallization under conditions of rapid cooling (skeletal and plumose clinopyroxene; dendritic plagioclase), and quenching (glass). Thus, crystallization and quenching of the interstitial liquid in the lower part of the flow precluded further settling and concentration of olivine.

The lack of vesicles in this sequence may indicate deposition in a relatively deep water environment.

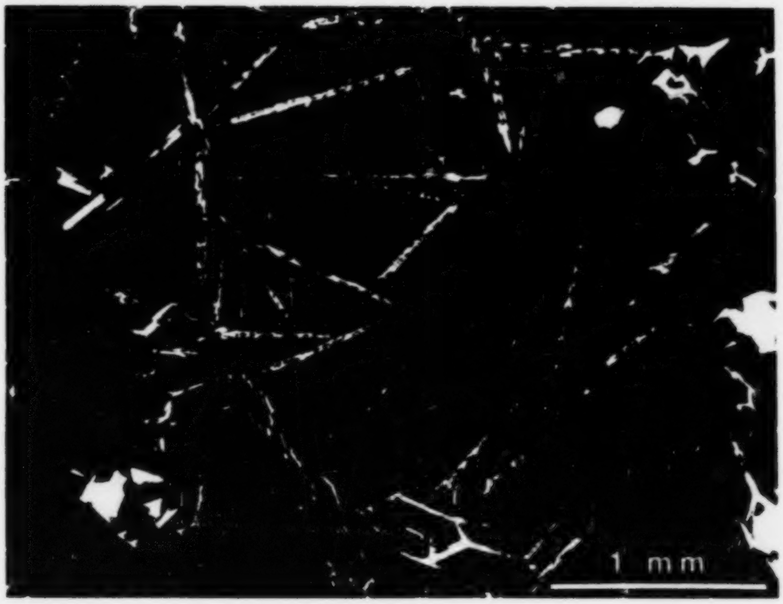


PLATE 68: Hopper and ornamental chain olivine crystals in fine grained, plumose, frond-like clinopyroxene groundmass. Note how ornamental chain olivine crystals extend from the pyramidal terminations of some hopper olivine crystals. Olivine has been replaced by fine grained chlorite. Columnar jointed upper part, layered flow, Middle zone, Upper volcanic formation, Otter Falls section, Stupart River (03-76-92-14) PL.

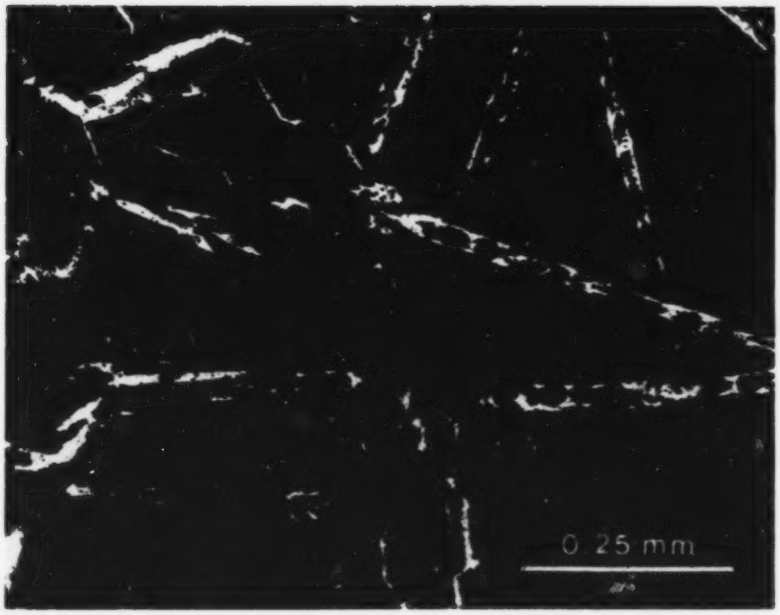


PLATE 69: Detail of hopper olivine with ornamental chain extending from pyramidal termination seen in Plate 68. PL.

FOX RIVER NORTH 2 SECTION

A series of pillowed olivine clinopyroxenites, and intercalated layered flows is exposed in discontinuous outcrop in the Fox River north 2 section (Fig. 3). The pillows are elongate to elliptical in outline, display a substantial range in size (from 20 cm elliptical masses up to 3 x 1 m elongate varieties), and are very tightly packed, with successive pillows being tightly molded to each other. There is consequently little interpillow space. Small interpillow spaces at pillow triple junctions are filled with quartz ± carbonate ± chlorite. Some elongate pillows are mattress-like, with their undersides conforming perfectly with the topography of the underlying pillows (Plate 70). The pillows are commonly variolitic, and some have well-developed quartz ± carbonate-filled cavities in their upper part. The cavities are identical to those found in pillows of the Lower volcanic formation pillowed zone previously described. Pillow rims range up to 4 cm wide, and vesicles are absent.

The rocks are dominantly composed of aggregates and clusters of polyhedral and hopper-shaped olivine, in a delicate, frond-like, plumose clinopyroxene groundmass (Plates 71 and 72). Olivine also occurs as elongate, ornamental chain-like crystals. Olivine is always present, and its content is variable and ranges up to 40 percent. The frond-like clinopyroxene occurs as radiate sprays of fibre-like crystals in some rocks. Disseminated, euhedral, red-brown chromite is commonly associated with altered olivine crystals. Irregularly-shaped sulphide grains are a common, though not abundant disseminated phase.

PLATE 70: Mattress pillow, olivine clinopyroxenite pillowed flow. Note how pillow perfectly conforms to topography of the underlying surface. Tops to the right. Repellant can is 15 cm long. Middle zone, Upper volcanic formation, Fox River north 2 section.

Two pillowed units display unusual assemblages and textures. One contains polyhedral olivine crystals, and irregularly-shaped laths, prisms, and skeletal crystals of clinopyroxene as suspended phases in a groundmass of fine grained, plumose tremolite replacing an original glass (Plates 73 and 74). Clusters of euhedral chromite crystals are associated with the olivine crystals. The other unusual unit consists of numerous, randomly disposed, skeletal clinopyroxene segments, and hopper-shaped olivine crystals, in a groundmass originally composed of dendritic to spherulitic plagioclase with intergrown clinopyroxene. The two units represent the only known departure from the more common olivine clinopyroxenite pillowed flows. The compositions and textures of these units are similar to some massive flows, and indicate that the lava giving rise to the pillows consisted of a fluid phase, and a suspended phase or phases. These pillows might represent the distal terminations of massive flows.

In the olivine clinopyroxenites, olivine crystals have been pseudomorphously replaced by chlorite ± quartz ± carbonate ± epidote, and clinopyroxene is preserved. Epidote is not common, and occurs as small discrete crystals associated with chlorite. In one thin section, epidote occurs in this fashion, and pumpellyite occurs as an alteration of plagioclase. The presence of epidote may indicate a local aberration of very low grade metamorphic conditions to slightly higher temperature conditions.

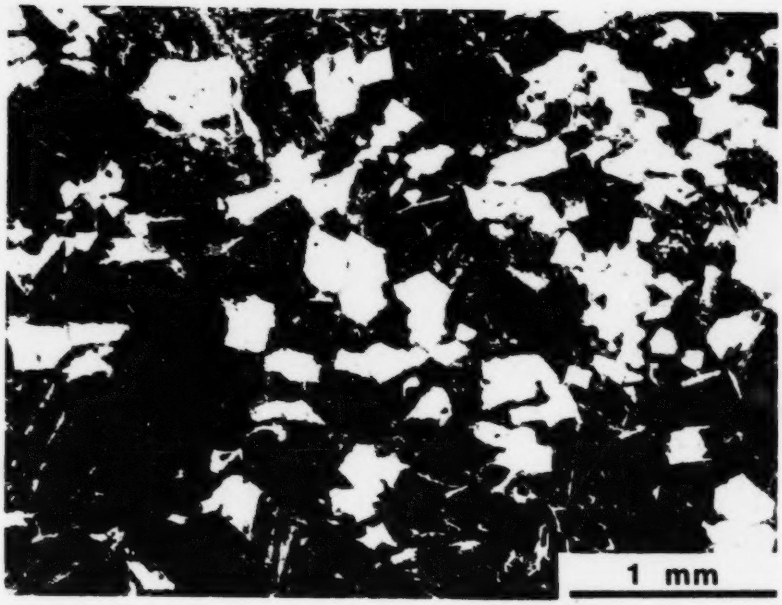
In the units displaying the unusual textures and compositions, olivine has been replaced by chlorite + tremolite ± quartz ± carbonate ± epidote. Original plagioclase crystals have been replaced by albite ± chlorite ± quartz ± sphene ± pumpellyite ± tremolite.

Two poorly exposed massive flows were encountered in this outcrop section. The flows are similar, and are composed of a lower cumulate zone, and an upper fine-grained zone. The lower cumulate zones contain suspended olivine and clinopyroxene, in a fine grained groundmass composed of dendritic to spherulitic plagioclase, with intergrown clinopyroxene. The suspended olivine is euhedral with slightly rounded terminations, whereas the suspended clinopyroxene is irregularly shaped and zoned, and some of the crystals are skeletal. Fine grained, euhedral, red-brown chromite, and irregularly-shaped sulphide grains are rare disseminated phases.

The two flows have upper zones of slightly different compositions and textures. In one, the upper zone consists of numerous clinopyroxene skeletal segments (up to 3 mm long), and scattered clusters of hopper-shaped olivine crystals in a groundmass originally composed of dendritic plagioclase and clinopyroxene (Plates 75 and 76). In the other, the upper zone consists of randomly oriented clinopyroxene skeletal segments, and hopper-shaped olivine, in a very fine grained groundmass interpreted to represent altered glass. There is a substantial range in the grain size of the clinopyroxene segments, which occur as clusters or aggregates, and these features give rise to a heterogeneous appearance in thin section.

The layered flow rocks are recrystallized with olivine being completely replaced by chlorite + tremolite ± epidote, and plagioclase being replaced by albite ± chlorite ± quartz ± sphene ± pumpellyite.

PLATE 71: Clusters of polyhedral and hopper olivine crystals in a matrix composed of groups of subparallel ornamental chain clinopyroxene crystals and coarse plumose clinopyroxene. Olivine has been replaced by chlorite. Pillowed olivine clinopyroxenite, Middle zone, Upper volcanic formation, Fox River north 2 section, Fox River (03-69-243) PL.



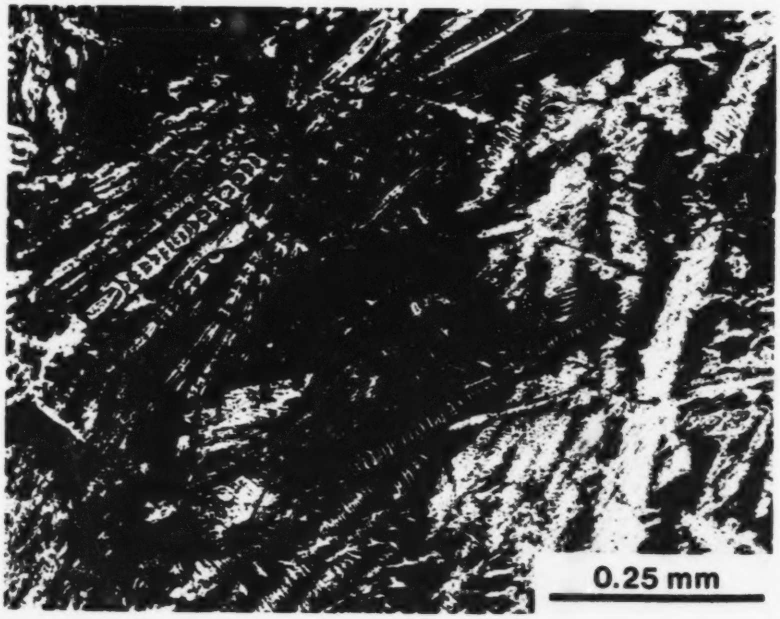
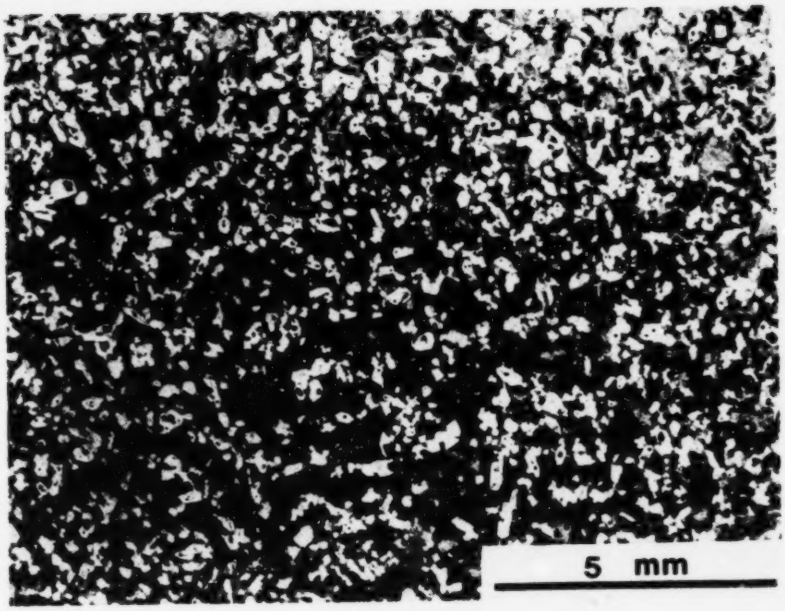


PLATE 72: Detail of ornamental chain clinopyroxene crystals and plumose, fibre-like clinopyroxene of groundmass seen in Plate 71. PL.

PLATE 73: Polyhedral olivine and skeletal clinopyroxene as partly cumulus (suspended) crystals in a groundmass of altered glass. Some of the clinopyroxene crystals have hollow cores. Olivine has been replaced by chlorite and tremolite. Glass has been altered to very fine grained, fibre-like amphibole. Opaque minerals within olivine crystals are magnetite ± pyrrhotite. Pillowed olivine clinopyroxenite, Middle zone, Upper volcanic formation, Fox River north 2 section, Fox River (03-76-111) PL.



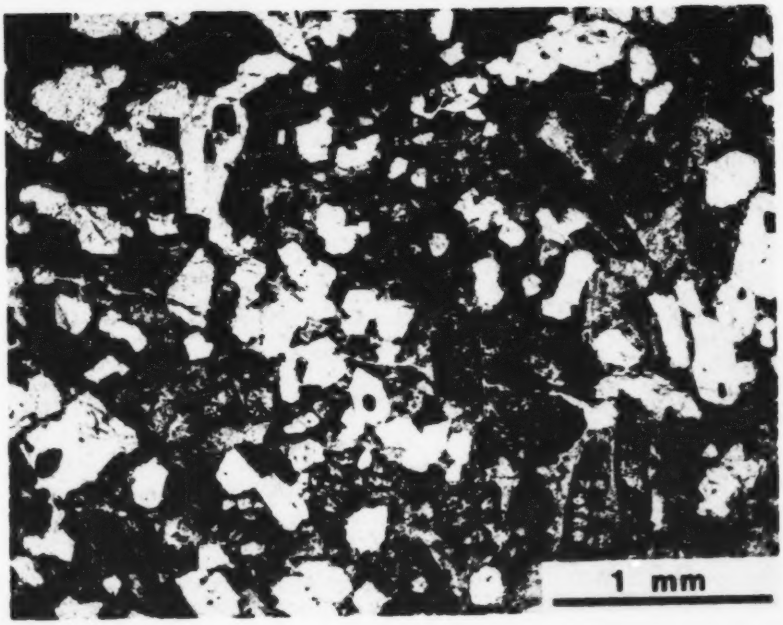
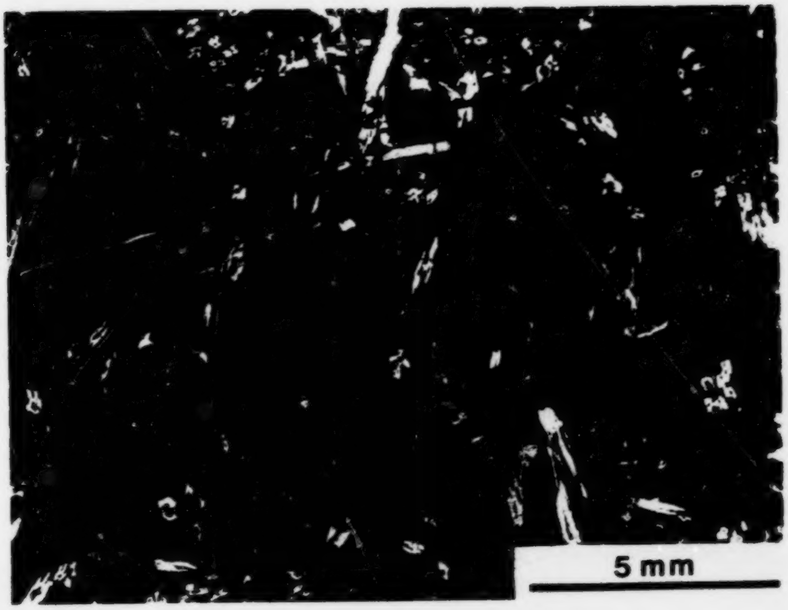


PLATE 74: Partly cumulus (suspended) polyhedral olivine crystals and irregular prisms and skeletal clinopyroxene crystals in a groundmass of altered glass. Opaque minerals in olivine crystals are magnetite and chromite. Pillowed olivine clinopyroxenite, Middle zone, Upper volcanic formation, Fox River north 2 section, Fox River (03-76-111) PL.

PLATE 75: Clusters of skeletal clinopyroxene segments, some individuals reach 3 mm in length. Rock also contains clusters of hopper and polyhedral olivine crystals (not seen here). Groundmass is composed of an intrafasciculate intergrowth of dendritic clinopyroxene and plagioclase crystals. Upper part, layered flow, Middle zone, Upper volcanic formation, Fox River north 2 section, Fox River (03-76-110-3) XN.



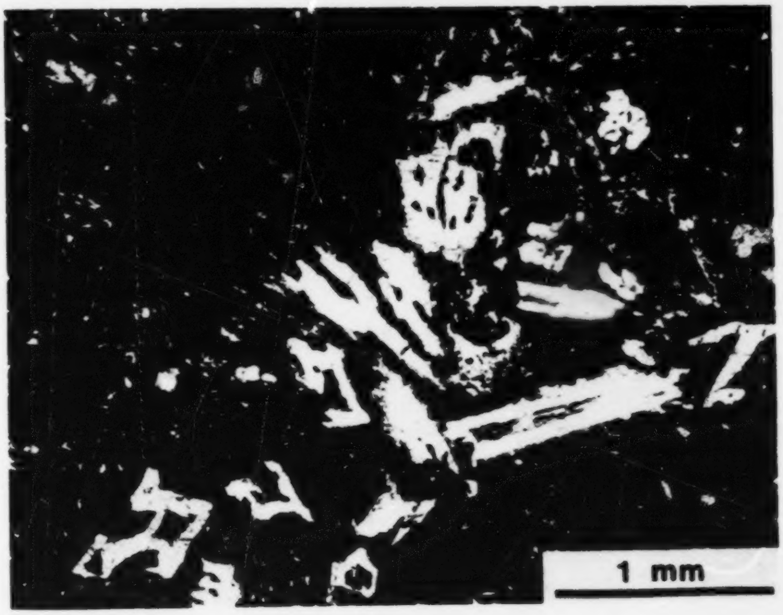


PLATE 76: Suspended skeletal clinopyroxene segments in a groundmass composed of an intergrowth of fine grained, dendritic clinopyroxene and plagioclase. Polyhedral and hopper olivine is also a suspended phase (does not show here). Upper part, layered flow, Middle zone, Upper volcanic formation, Fox River north 2 section, Fox River (03-76-110-3) XN.

The sequence of rocks exposed in Fox River north 2 section is similar to the suite of pillowed and layered flows exposed in the Otter Falls section on the Stupart River, 20 km to the east. These two outcrop areas are grouped together to form the Middle zone of the Upper volcanic formation. This zone is distinguished by being composed dominantly of olivine clinopyroxenite pillowed flows, and intercalated layered flows. The layered flows consist of two zones, a lower olivine-bearing cumulate zone and an upper, fine-grained zone, dominated by skeletal crystals in an originally glassy matrix. These flows contrast with the more complex layered flows of the Lower zone.

The Middle zone of the Upper volcanic formation is similar to the Middle pillowed zone of the Lower volcanic formation in that it comprises pillowed olivine clinopyroxenite flows and intercalated massive and layered flows. It differs, however, in apparently having a greater proportion of layered flows, and in being only about one half as thick.

JACKFISH FALLS SECTION, STUPART RIVER

A sequence of massive and pillowed flows is exposed over a distance of 380 m in the Jackfish Falls section on the Stupart River (Fig. 21). The Jackfish Falls section is 400 m+ north of the Otter Falls section, and a change in the nature of the flows takes place between these two outcrop areas. The Otter Falls section consists dominantly of pillowed olivine clinopyroxenite separated by three layered flows, whereas the Jackfish Falls section consists of an almost equal abundance of pillowed and massive basalt.

The pillowed flows are somewhat undistinguished, cavities are present though not abundant, vesicles and radial fractures are rare, and variolitic flows have not been observed. Pillow rims range from 1 to 2 cm. The pillows display a large range in size, from 10 cm spherical masses, to pillows up to 2.5 m long by 1 m wide. Most pillows are elongate (Plate 77), and the length to width ratio averages 2:1. The volume of intrapillow space is greater than in olivine clinopyroxenite pillows, and the space is occupied by hyaloclastite breccia (Plate 78) and quartz-carbonate.

The rocks display a range of textural relationships in thin section, due to the variation in clinopyroxene morphology. Clinopyroxene occurs as coarse, frond-like, plumose crystals, with randomly dispersed skeletal segments, some of which are joined to form delicate, ornamental chain-like crystals (Plate 79).

PLATE 77: Pillowed basalt. Note elongate nature of pillows and small open spaces at triple junctions. Pillow at right foreground is 80 cm long by 30 cm wide. Upper zone, Upper volcanic formation, Jackfish Falls, section, Stupart River.

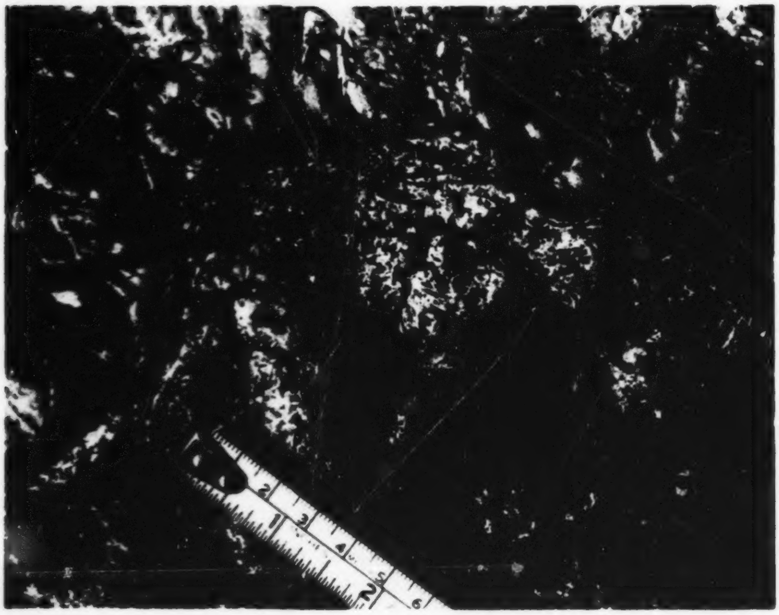


PLATE 78: Detail of hyaloclastite breccia developed in pillowed basalt triple junction. Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River.

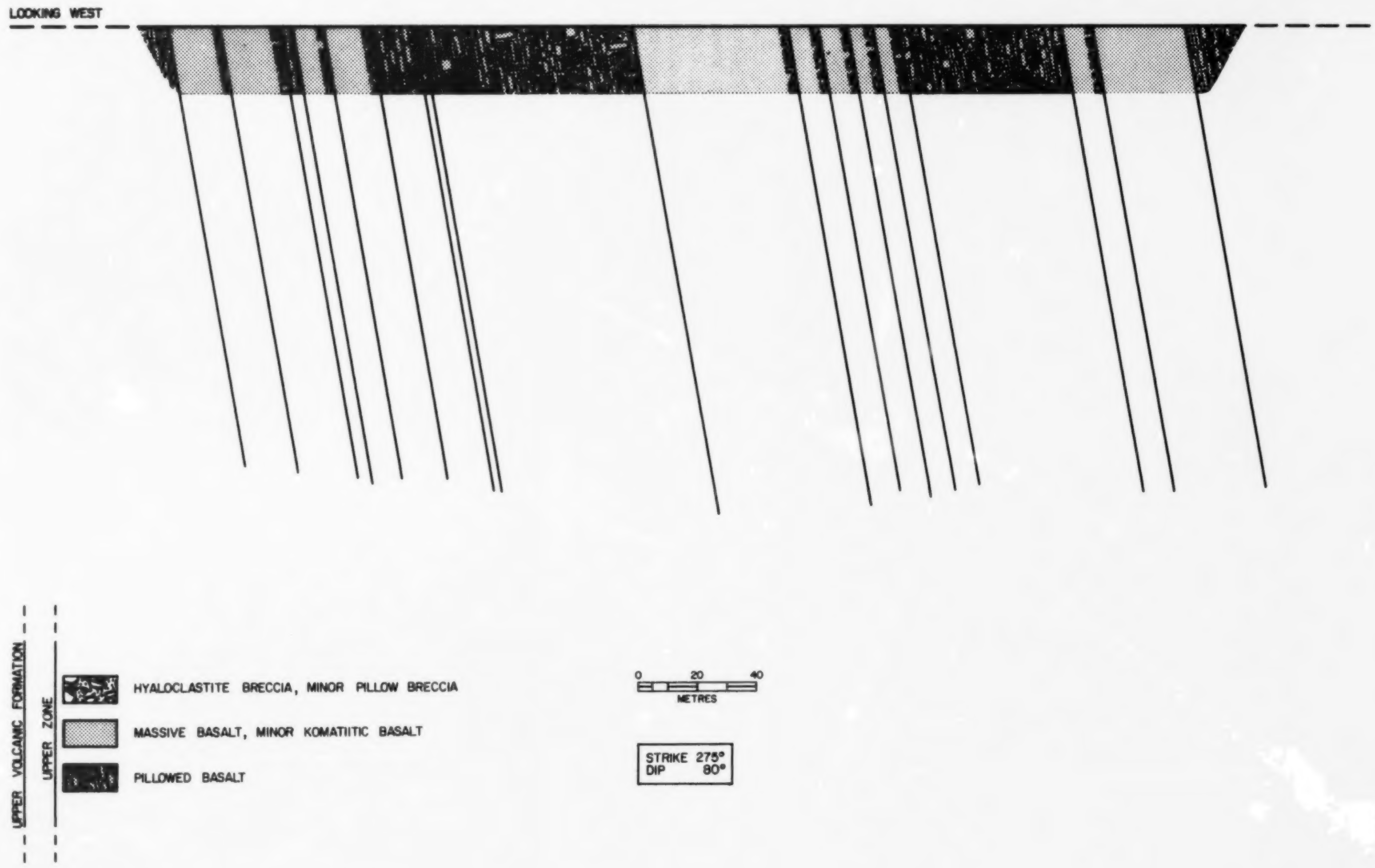

LOOKING WEST
UPPER VOLCANIC FORMATION
UPPER ZONE
HYALOCLASTITE BRECCIA, MINOR PILLOW BRECCIA
MASSIVE BASALT, MINOR KOMATIITIC BASALT
PILLOWED BASALT
0
20
40
METRES
STRIKE 275°
DIP 80°

FIGURE 21: Jackfish Falls section, Stupart River

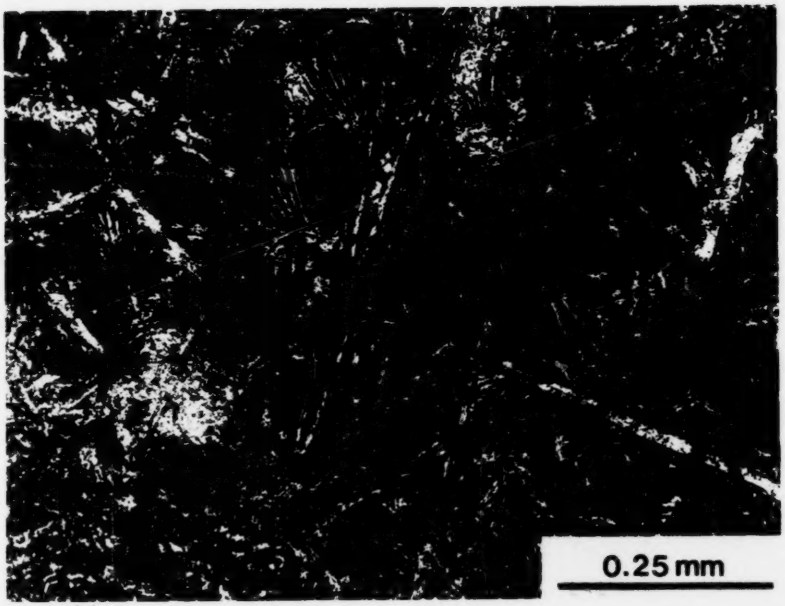


PLATE 79: Coarse plumose, frond-like clinopyroxene and ornamental chain clinopyroxene forming a groundmass to skeletal clinopyroxene crystals and lath-like plagioclase. Pillowed basalt flow, Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River (03-76-108) PL.

It also occurs as radially disposed sprays of fibre-like crystals. In some rocks, clinopyroxene occurs as straight to curving, blade-like crystals with serrated edges, some of which are grouped into subradially disposed crystals (Plate 80). Some elongate clinopyroxene crystals with splayed, divergent terminations develop into dendritic to spherulitic crystals with intergrown plagioclase. Plagioclase occurs as randomly oriented laths, clusters of euhedral crystals, and dispersed skeletal segments. The most common textural variety is one in which laths and clusters of euhedral plagioclase, and skeletal plagioclase segments are dispersed in a groundmass of radiating sprays of fibre-like clinopyroxene crystals (Plate 81). Hopper-shaped olivine crystals are rare, and disappear altogether toward the top of the sequence. Discrete, irregularly-shaped, fine grained sulphide is sporadically distributed throughout the sequence.

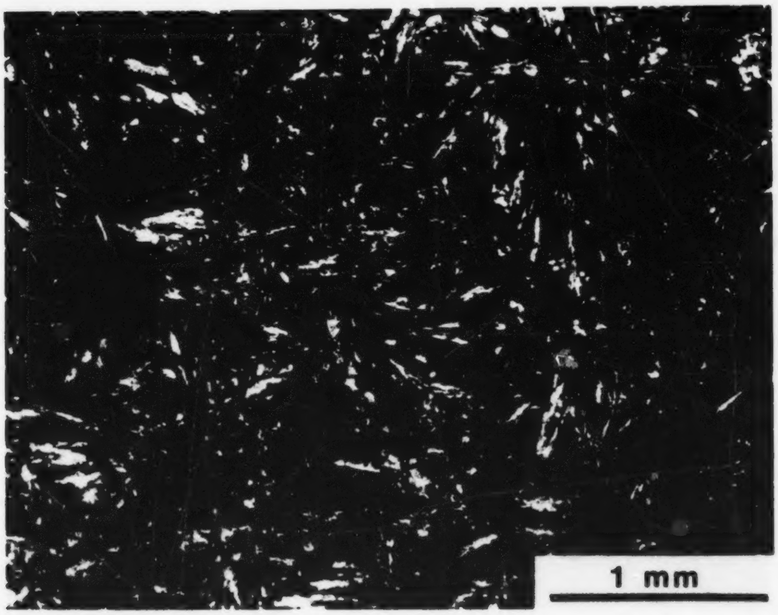
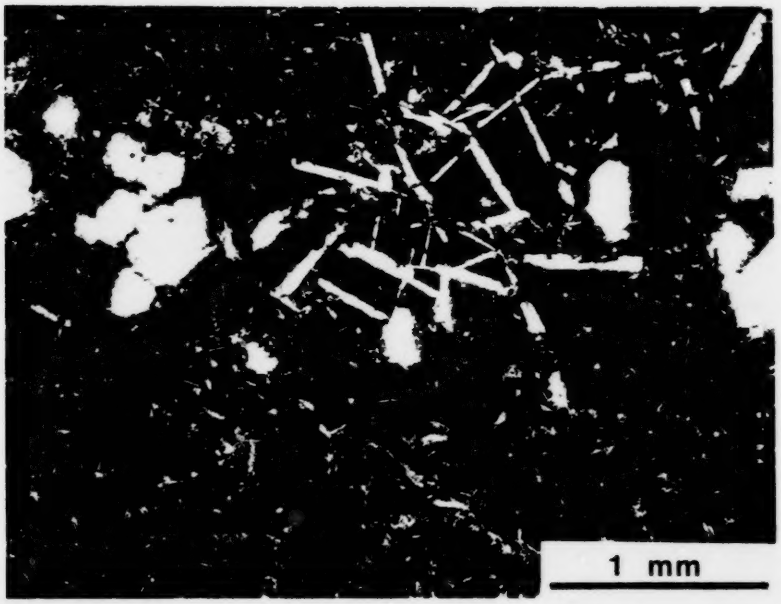


PLATE 80: Stubby clinopyroxene blades, many with splayed, divergent terminations and some randomly disposed skeletal clinopyroxene crystals, with lath-like plagioclase crystals. Pillowed basalt flow, Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River (03-76-107-2) XN.

PLATE 81: Clusters of euhedral, lath-like and prism-like plagioclase crystals in a groundmass of radiating, fibre-like clinopyroxene crystals. Pillowed basalt flow, Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River (03-76-101) PL.



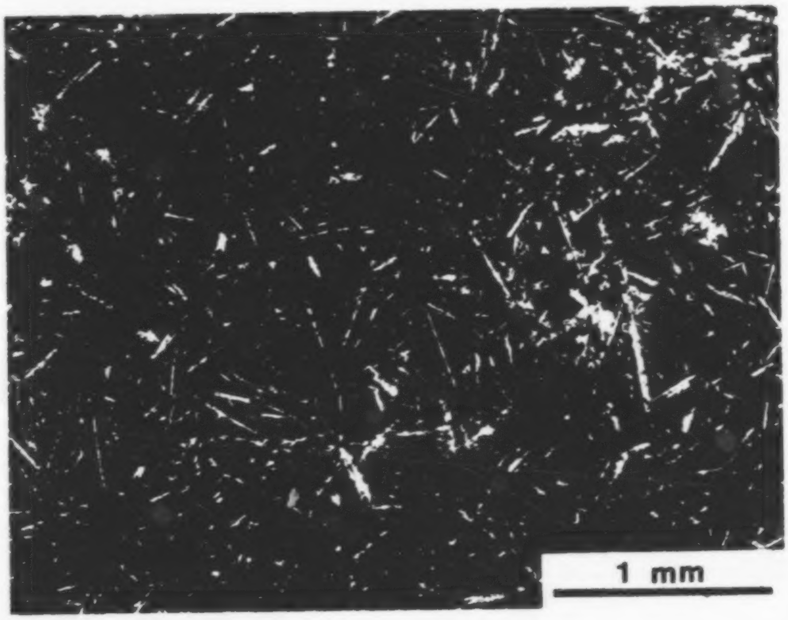
Clinopyroxene is well preserved, whereas plagioclase is recrystallized to albite ± muscovite ± chlorite ± sphene ± quartz ± carbonate ± epidote. In addition, pumpellyite commonly replaces plagioclase. Prehnite is a common vein filling, and is usually associated with carbonate and quartz.

Massive flows are well exposed in the Jackfish Falls section, and are simple rather than layered. The lowest part of some flows is slightly more granular than the upper part, and such changes are gradational. The granular portion tends to be 1 to 2 m above the base of the flow, and never exceeds 2 m in thickness, even in the thickest flow. The massive flows are characterized by well-developed hyaloclastite flow top breccias (Plate 82).

PLATE 82: Contact between successive massive basalt flows. Hammer handle rests on hyaloclastite, flow-top breccia. Low area occupied by boulders is a one pillow thick, pillowed basalt flow. Base of next overlying massive basalt flow occupies the left foreground of the photograph. Hammer is 30 cm long. Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River.

The rocks are distinguished by an abundance of plagioclase as lath-like crystals, and by an almost total absence of olivine (Plates 83 and 84). Clinopyroxene is highly variable, and ranges from straight to curving blade-like crystals, as randomly disposed individuals, groups of parallel crystals, and subradially disposed crystal groups. It also occurs as ornamental, chain-like crystals, as fine to coarse frond-like, plumose crystals, and as delicate, radiating, fibre-like crystals. In the latter, some individual fibres are constructed of joined skeletal segments. Dendritic and spherulitic crystals have also been observed. Much of the clinopyroxene possesses clear central portions, and distinctly brownish margins. Plagioclase occurs dominantly as lath-like crystals; however, near the base and top of some flows, skeletal plagioclase crystals and acicular, spear-like plagioclase crystals occur in a frond-like, plumose clinopyroxene groundmass.

PLATE 83: Randomly disposed plagioclase laths in a groundmass composed of frond-like, plumose and ornamental chain clinopyroxene crystals. The original plagioclase has been replaced by chlorite + muscovite + sphene although a few original labradorite crystals are preserved. Upper part of massive basalt flow, Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River (36-75-250-1b) PL.



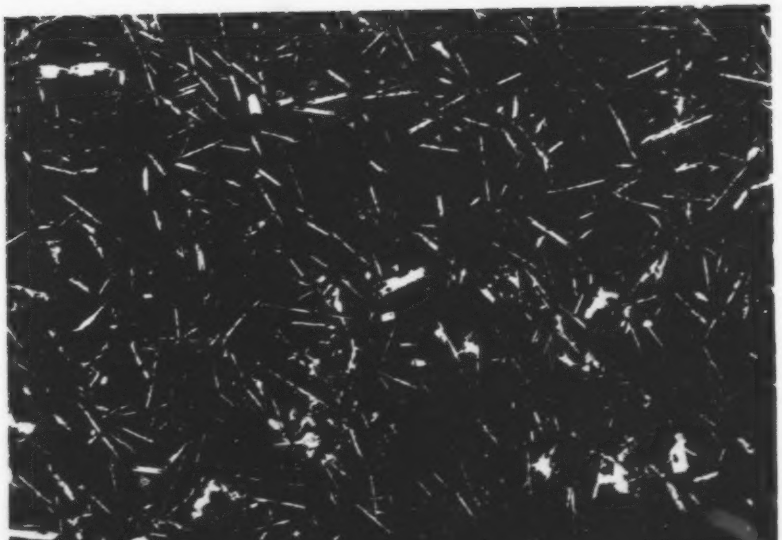


PLATE 84: Randomly disposed skeletal plagioclase crystals, many with swallow-tail terminations, in a groundmass of frond-like, plumose clinopyroxene. Base of massive basalt flow, Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River (36-75-250-2) PL.

One 50 m thick, massive flow appears almost featureless in outcrop, yet displays regular textural changes from base to top. Near the flow base, clinopyroxene occurs as large (up to 2 mm) irregularly-shaped, plate-like crystals, with numerous inclusions of randomly oriented plagioclase laths (Plate 85). The large clinopyroxene crystals resemble aggregates of irregularly-shaped individuals with similar optical orientation. Each individual possesses patchy to sweeping extinction, and many appear to be crudely zoned. These features give rise to very complex extinction patterns in the larger aggregate crystals. Some of the aggregate crystals display a radial pattern, and form dendritic to spherulitic crystals (Plate 86). A number of aggregate, dendritic crystals have overgrown lath-like plagioclase crystals that now form the cores of the complex crystals. The dendritic and spherulitic clinopyroxene crystals appear to be the textural analogues of the dendritic and spherulitic plagioclase crystals previously described. The groundmass is composed of fine grained, irregularly-shaped clinopyroxene, and randomly disposed plagioclase laths.

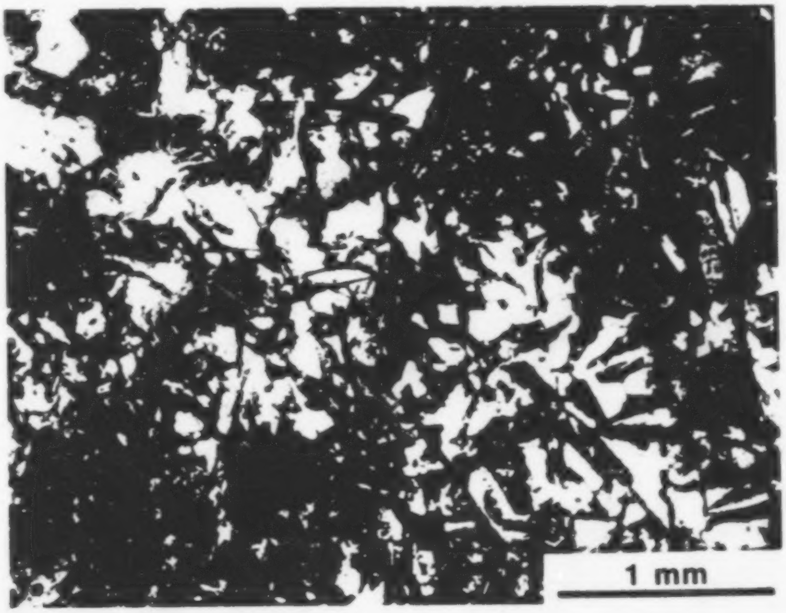


PLATE 85: Irregularly-shaped, poikilitic clinopyroxene crystals with numerous inclusions of lath-like plagioclase crystals. A few original labradorite crystals are preserved. Lower part, massive basalt flow, Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River (36-75-250-4a) XN.

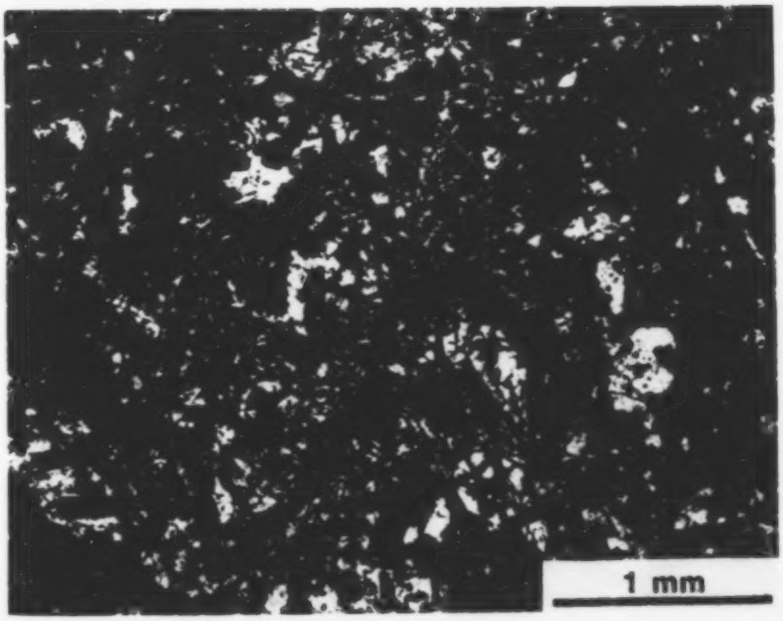


PLATE 86: Dendritic clinopyroxene crystal with splayed, divergent termination. The groundmass is composed of plagioclase laths and prism-like crystals and hour-glass zoned clinopyroxene crystals. Basal part of massive basalt flow, Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River (36-75-250-4f) PL.

The remainder of the lower part of the flow, and the middle part of the flow contain randomly disposed plagioclase laths, and irregularly-shaped clinopyroxene crystals. The clinopyroxene crystals have brownish rims and are strongly zoned, hour-glass and sector zones being observed. Dendritic to spherulitic clinopyroxene crystals, intergrown with plagioclase, occur in the groundmass. A rock in the middle part of the flow contains, aggregate, porphyritic clinopyroxene crystals similar to the basal part of the flow (Plate 87). Unlike the basal part of the flow, however, the rock also contains elongate, blade-like, twinned clinopyroxene crystals (Plate 88).

The upper part of the flow is characterized by elongate, blade-like clinopyroxene crystals (up to 1.5 mm long) with serrated edges, and a medial line along the length of most crystals (Plates 89 and 90). Some of the blade-like crystals occur as radially developed sprays. Dendritic to spherulitic clinopyroxene is distinguished by brownish rims. Plagioclase occurs as randomly disposed, lath-like crystals. A rock in the upper part of the flow consists of randomly oriented, fine grained, lath-like crystals, skeletal crystal segments, and clusters of euhedral crystals of plagioclase in a fine grained groundmass of frond-like, plumose, and ornamental chain-like clinopyroxene crystals.

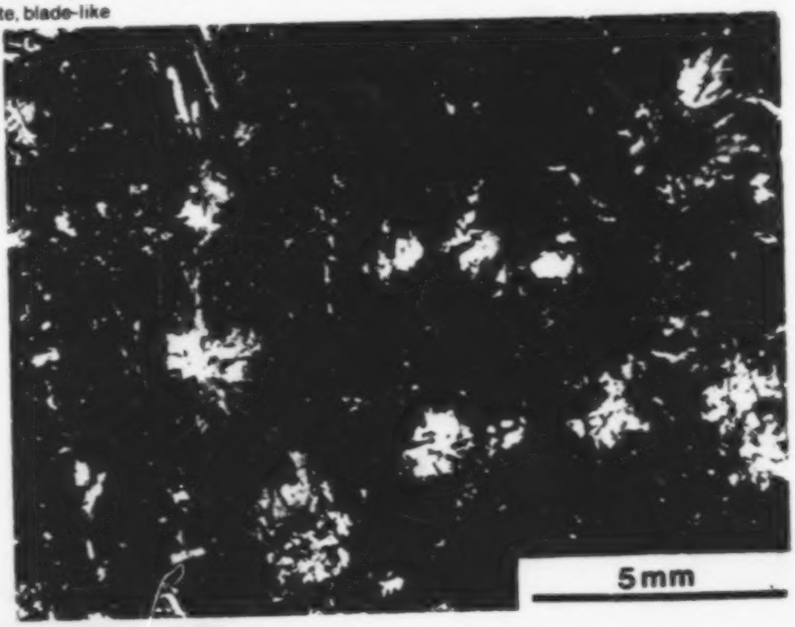


PLATE 87: Irregularly-shaped, poikilitic clinopyroxene crystals with inclusions of lath-like plagioclase crystals. Groundmass is composed of plagioclase laths and fine grained, irregularly-shaped clinopyroxene crystals. Middle part of massive basalt flow, Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River (36-75-250-4g) XN.

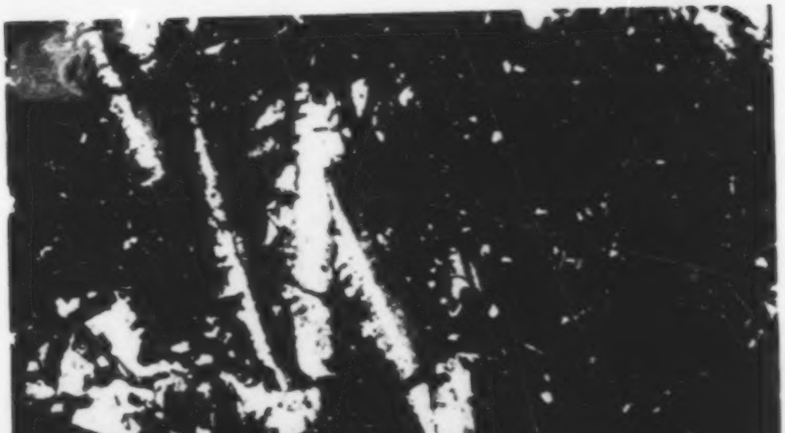


PLATE 88: Elongate, blade-like clinopyroxene crystals with serrated edges and twin plane running the length of the crystals. The groundmass is composed of plagioclase laths and irregularly-shaped, equidimensional, zoned, clinopyroxene crystals. Middle part of massive basalt flow, Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River (36-75-250-4g) XN.

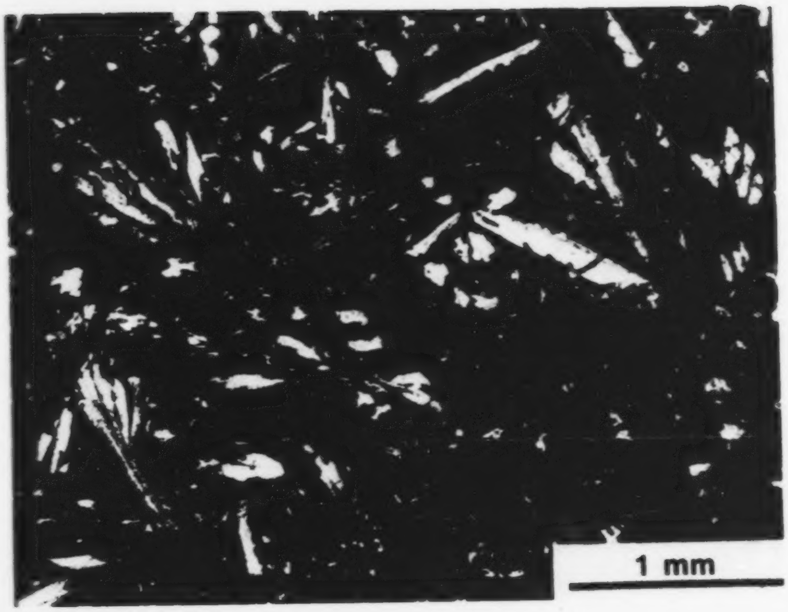


PLATE 89: Elongate, blade-like clinopyroxene crystals, some with splayed, divergent terminations. Groundmass is composed of irregular and dendritic clinopyroxene-plagioclase intergrowths producing intrafasciculate textures. Upper part of massive basalt flow, Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River (36-75-250-4i) XN.

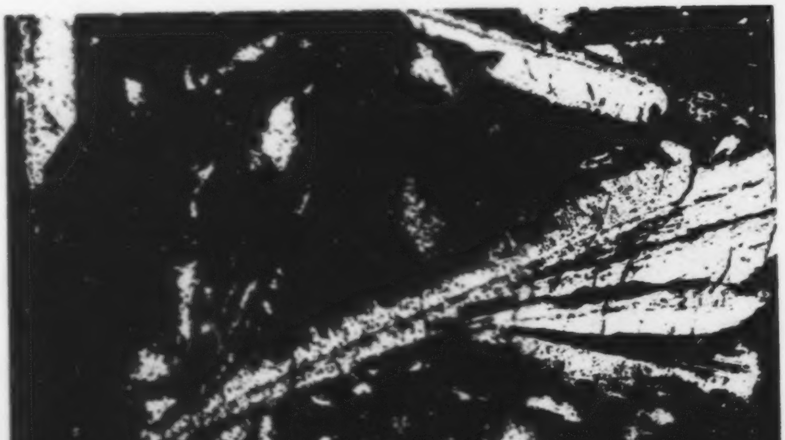


PLATE 90: Elongate, blade-like clinopyroxene crystal with splayed, divergent termination. Groundmass is composed of irregular and dendritic intergrowths between clinopyroxene and plagioclase producing intrafasciculate textures. Upper part of massive basalt flow. Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River (36-75-250-4i) XN.

The massive flows possess hyaloclastite flow top breccias. The breccias appear to form a continuous phase in the uppermost part of the flow, and they commonly contain blocks, and irregularly-shaped protrusions of unbrecciated lava (Plate 91). Progressing upward to the flow top from its first appearance, the ratio of breccia to unbrecciated basalt increases dramatically. The brecciated portion of the flow seldom exceeds 3 m in thickness. The hyaloclastite breccias are a chaotic mixture of subrounded fragments and globules, which range from several millimetres to several centimetres, are vitreous, break with a subconchoidal fracture, and most have a narrow whitish rim (Plate 92). Some of the larger fragments are fractured, and the fractures are enhanced by the same whitish material that rims the fragments. The fragments are dominantly dark olive green, although light green, buff, and honey brown fragments have been observed. The slightly granular matrix is mottled olive green, the mottling being caused by whitish patches, lenses and discontinuous veins. The contact between the breccia and massive basalt is sharp and distinct. A 3 m thick breccia, separating successive massive flows, consists of irregularly-shaped, pillow-like masses in a matrix of hyaloclastite breccia (Plate 93). Many of the pillow-like masses possess successive rims. A one pillow thick pillowed zone has been observed at the base of one massive flow, and apparently separates successive massive flows.

PLATE 91: Hyaloclastite breccia, top of massive basalt flow. Breccia forms a continuous phase, and contains areas of unbrecciated basalt. Pen is 15 cm long. Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River.

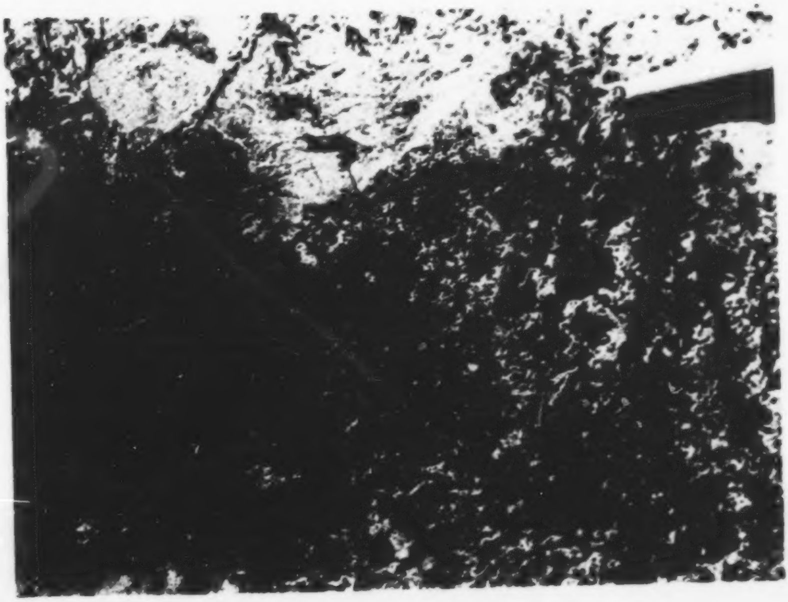
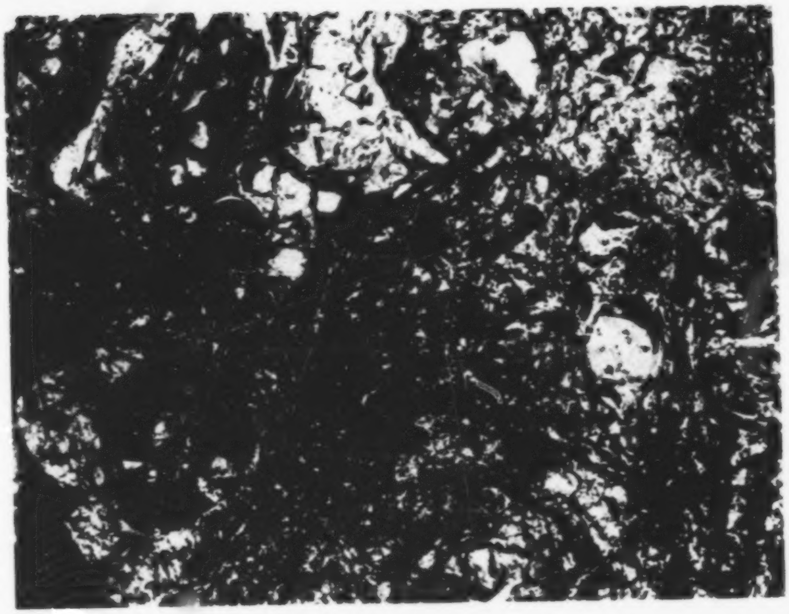


PLATE 92: Detail of hyaloclastite breccia seen in Plate 91. Note subrounded fragments and shards. Pen top at upper right points to small, irregular area of unbrecciated basalt. Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River.

PLATE 93: Pillow breccia. Basalt pillows and pillow fragments in an hyaloclastite matrix. Zoned margins due to alteration. Lens cap is 6 cm in diameter. Upper zone, Upper volcanic formation, Jackfish Falls section, Stupart River.



Clinopyroxene is well preserved throughout the sequence of massive flows, whereas plagioclase ranges from being partially preserved, to being completely recrystallized. Partially preserved plagioclase crystals (labradorite) are poikilitically enclosed in the large, aggregate clinopyroxene crystals. The clinopyroxene crystals have armoured the plagioclase crystals, and thereby partly protected them from recrystallization. The lath-like, groundmass plagioclase has been completely replaced by albite ± muscovite ± chlorite ± sphene ± quartz ± carbonate ± pumpellyite ± epidote. Pumpellyite is sporadically distributed throughout the sequence, and it pseudomorphously replaces some plagioclase laths. Prehnite is common though not abundant, and occurs dominantly as vein fillings with quartz and carbonate. Other veinlets are composed of quartz ± carbonate ± epidote ± sulphide.

Pumpellyite, prehnite and epidote have been noted occurring together in a number of rocks. Several examples of pumpellyite and epidote sharing mutual boundaries have been observed, although no clear-cut relationship between these minerals has been determined. In some rocks pumpellyite is widespread, and epidote is rare, and poorly formed, in other rocks, crystals of epidote occur as vesicle fillings with quartz, carbonate and chlorite. One example of pumpellyite cutting epidote in a veinlet has been observed. The presence of epidote in rocks that otherwise possess characteristics indicating that they suffered only very low grade metamorphism is anomalous. Epidote may have formed in response to a later metamorphic event at a slightly elevated temperature; however, a lack of clear-cut relationships between epidote, and pumpellyite, and prehnite makes this explanation seem unlikely.

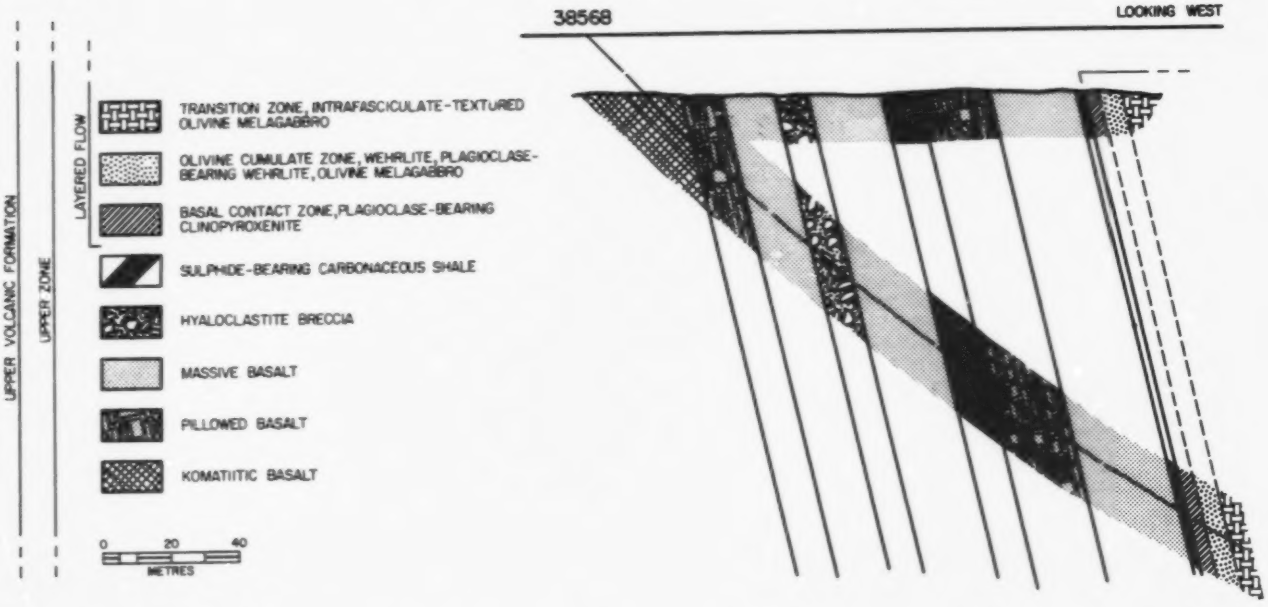
The flows of the Jackfish Falls section are substantially different from the flows of the Otter Falls section, some 400 m to the south. They represent crystallization from lava that contained little normative olivine, and abundant normative plagioclase. The simple nature of the massive flows implies that the lava was largely crystal-free at eruption, and that significant crystal growth after nucleation was rare. Although skeletal crystals are present, they are very much less abundant than in the Otter Falls section, indicating that crystallization took place under equilibrium conditions, and that crystallization under conditions of supercooling was much more restricted.

DRILL HOLE 38568

A succession of flows, ranging in composition from komatiitic basalt to basalt, including a section dominated by hyaloclastite breccia, is exposed in drill hole 38568 (Fig. 22). The hole terminates in a sequence of ultramafic rocks, that could be the base of a layered flow. Sulphide-bearing, carbonaceous shale separates successive flows in two places.

The upper part of the komatiitic flow is characterized by radiate sprays of elongate, straight to curving, blade-like clinopyroxene crystals up to 1.0 mm in length. The crystals display sweeping extinction, and many have a medial line extending along their length. A few, slender plagioclase crystals also occur as a suspended phase. The pyroxene and plagioclase crystals occur in a groundmass of dendritic plagioclase and clinopyroxene. The overall texture is similar to clinopyroxene spinifex texture, but is finer grained. The rock is considered to be komatiitic basalt on the basis of its texture.

Basalts are distinguished by having recognizable lath-like or prismatic plagioclase crystals as a suspended phase. Straight to curving, blade-like clinopyroxene crystals, some of which are arranged as radiating, divergent sheaf-like masses, also occur as a suspended phase. Clusters of hopper-shaped olivine crystals have been observed in a few rocks. The groundmass was originally composed of fine grained dendritic plagioclase and clinopyroxene.


38568
LOOKING WEST
UPPER VOLCANIC FORMATION
UPPER ZONE
LAYERED FLOW
TRANSITION ZONE, INTRAFASCICULATE-TEXTURED OLIVINE MELAGABBRO
OLIVINE CUMULATE ZONE, WEHRLITE, PLAGIOCLASE-BEARING WEHRLITE, OLIVINE MELAGABBRO
BASAL CONTACT ZONE, PLAGIOCLASE-BEARING CLINOPYROXENITE
SULPHIDE-BEARING CARBONACEOUS SHALE
HYALOCLASTITE BRECCIA
MASSIVE BASALT
PILLOWED BASALT
KOMATIITIC BASALT
0
20
40
METRES

DIP OF UNITS BASED ON CORE AXIS ANGLE OF 40°
(AVERAGE LAMINATION OF CARBONACEOUS SHALE)

FIGURE 22: DDH 38568

A sequence of very fine grained rocks, composed of brownish, frond-like, plumose clinopyroxene, containing numerous, randomly oriented, skeletal plagioclase crystals is interpreted to represent pillowed basalt (Plate 94). Plagioclase crystals occur as clusters in some rocks, and the rocks are vesicular.

One basalt flow is capped or overlain by a 10 m thick hyaloclastite breccia. The breccia is characterized by numerous, dark greenish-brown to honey-brown to whitish-green, vitreous, irregularly-shaped, angular to subrounded fragments, and globules in a light greenish-brown, mottled, and somewhat granular groundmass (Plate 95). Most of the fragments have a narrow (1-2 mm) whitish haloe or selvedge, and all of the fragments have a globular shape, and these display a light rim surrounded by a darker rim (up to 2.0 mm). Much of the mottling of the groundmass is caused by

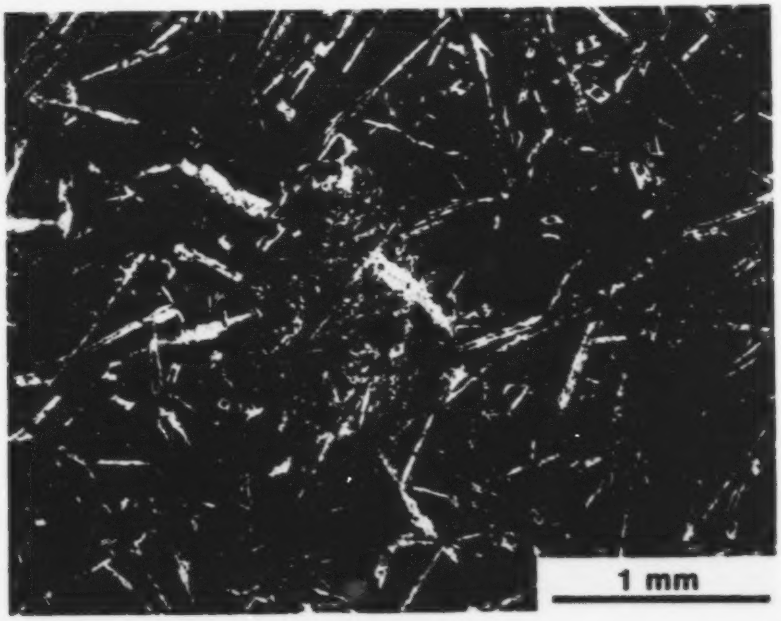


PLATE 94: Randomly disposed plagioclase skeletal segments in a groundmass of plumose, frond-like clinopyroxene. Possible pillow rim, basalt flow, Upper zone, Upper volcanic formation, DDH 38568 (38568-200) PL.

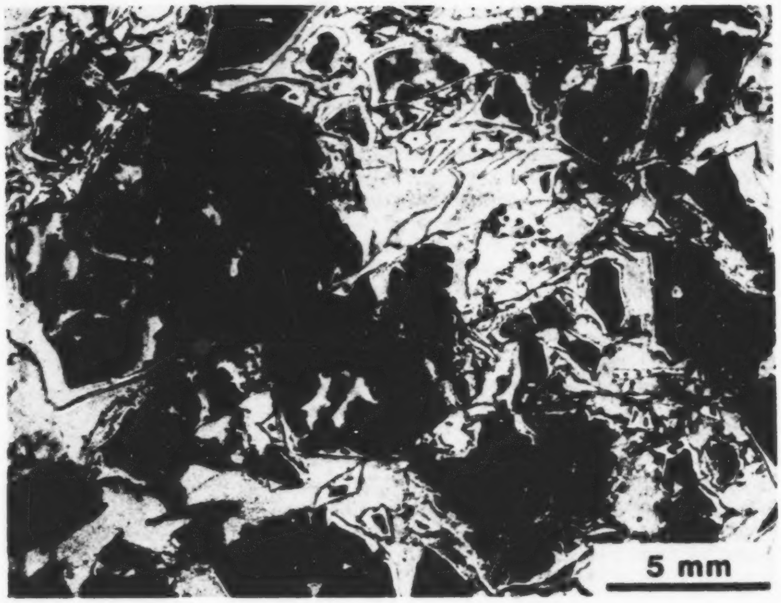


PLATE 95: Hyaloclastite breccia composed of irregular and shard-shaped pyroxenite and glass fragments. The clear, originally glassy material has been replaced by chlorite. Note the preserved flow lines in glassy fragment at the left of the photo. Hyaloclastite breccia. Upper zone, Upper volcanic formation, DDH 38568 (38568-310) PL.

irregular patches of the same whitish material that forms rims on fragments and globules. Some whitish-green fragments contain light olive green vitreous patches as inclusions. Some larger fragments, including globules, range up to 2 cm, and the rock has a heterogeneous appearance.

In thin section, some of the fragments occur as brownish to milky grey areas that have been identified by x-ray as diopside. The fine grained groundmass is composed of chlorite, and finely disseminated sphene. Calcite crystals form a disseminated phase in the groundmass. Pyrrhotite and minor chalcopyrite form disseminated, and discontinuous stringer-like masses in fragments and groundmass.

The overall appearance of the hyaloclastite breccia is similar to a much finer grained breccia observed in the glassy rims of some pillows, and in some interpillow spaces at pillow triple junctions. In these examples it appears that original contiguous glass became brecciated or granulated, and subsequently recemented by new glass. The brecciation was accomplished in a subaqueous environment, and by analogy, the hyaloclastite breccia is interpreted to represent subaqueous brecciation on a much larger scale. This agrees with a general mechanism for the formation of hyaloclastite (Macdonald, 1967), that involves the front and surface of a lava flow advancing beneath water, and being chilled to glass, and granulated into a mass of sandy-textured hyaloclastite. Macdonald stated that the hyaloclastite tends to protect the lava beneath it from contact with the water, and the lava flow expands beneath an increasing mass of hyaloclastite.

The peridotite at the base of the drill hole is completely recrystallized, and originally consisted of cumulus euhedral olivine, with slightly rounded terminations, and sporadically distributed clusters of euhedral chromite crystals. The groundmass, which originally composed 10 to 15 percent of the rock was probably dominantly clinopyroxene and plagioclase. The peridotite is overlain by a rock composed of suspended olivine and sector and hour-glass zoned clinopyroxene (Plate 96) in a groundmass of dendritic plagioclase and clinopyroxene.

Throughout the drill hole sequence, clinopyroxene is well preserved, and original basic plagioclase (> An_{50}) is preserved in one rock. Elsewhere, plagioclase has been altered to albite ± muscovite ± chlorite ± sphene ± quartz. Pumpellyite and prehnite have been observed replacing plagioclase, and prehnite also occurs as a partial filling of vesicles and veinlets, along with carbonate ± chlorite ± quartz.

In many rocks, clinozoisite occurs as an alteration of original olivine crystals, along with chlorite ± carbonate ± quartz. It is less common as an alteration of plagioclase in rocks that also contain pumpellyite and prehnite. It has been noted that several rocks have been observed, where the original basic plagioclase (>An_{50}) is partly preserved. It seems clear that clinozoisite must be unstable under the pressure-temperature conditions indicated for these rocks. In a similar fashion, tremolite has been noted as a partial replacement of olivine in rocks where pumpellyite and prehnite occur nearby in the sequence. In one example, tremolite and pumpellyite occur in the same thin section. The presence of tremolite is considered to be due to compositional control that overides the controls exerted by temperatures and pressure. Clinozoisite, by being associated dominantly with olivine, may also owe its existence to the influence of composition.

Olivine is replaced by talc ± tremolite ± chlorite ± magnetite, and plagioclase is replaced by chlorite ± sphene ± tremolite in the ultramafic rocks at the base of the drill hole.

FOX RIVER NORTH 3 SECTION

Pillowed and massive basalt flows are exposed in scattered outcrop in Fox River north 3 section (Fig. 3). The widely scattered nature of the outcrop precludes a detailed examination of the flows. The pillowed flows consist of well-formed, tear drop-shaped pillows with narrow rims (up to 1 cm). Vesicles are developed in a 6 to 8 cm wide zone around pillow peripheries (Plate 97). The rocks are pale greyish green, and are cut by closely spaced joints, rendering a blockly nature to the outcrop.

The rocks originally consisted of randomly oriented plagioclase laths (up to 1.0 mm long), and irregularly-shaped clinopyroxene grains. The clinopyroxene crystals are distinctly brownish, and display sweeping extinction. Many are strongly zoned. Plagioclase has been replaced by albite ± muscovite ± chlorite ± sphene ± carbonate + epidote. Pyrite occurs as very fine grained, widely dispersed disseminations. Vesicles are filled with quartz ± carbonate ± chlorite.

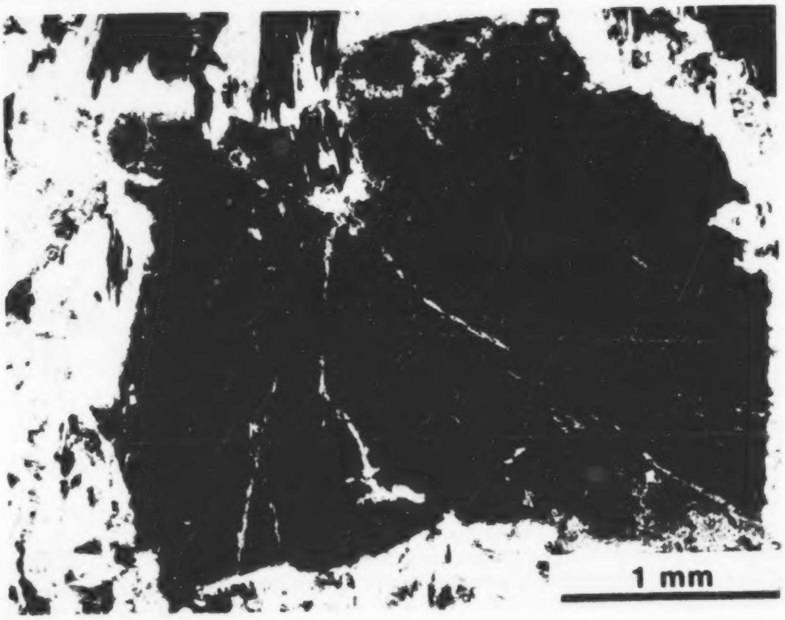


PLATE 96: Hour-glass zoned clinopyroxene crystal. Cumulus olivine-rich zone, layered flow, Upper zone, Upper volcanic formation, DDH 38568 (38568-800) XN.

PLATE 97: Pillowed basalt. Note tear drop shape, well-developed rims and vesiculated nature. Hammer is 30 cm long. Upper zone, Upper volcanic formation, Fox River north 3 section.

The massive flows are vesicular, grey green, and display the blocky jointing noted in the pillowed flows. The rock consists of stubby plagioclase prisms and equidimensional, but irregularly-shaped, clinopyroxene. The clinopyroxene grains are brownish, and display sweeping extinction. Plagioclase has been altered to albite ± chlorite ± muscovite ± sphene. Tremolite forms a very widely dispersed phase, as very fine grained crystals, possibly replacing plagioclase. Epidote is absent. The vesicles are filled with chlorite, and euhedral quartz crystals.

The pillowed and massive flows differ from other flows of the formation in being highly vesiculated. There is no evidence of crystal accumulation, nor is there evidence of non-equilibrium crystallization. The flows are basalts and represent lava from which plagioclase and clinopyroxene crystallized.

SUMMARY OF LITHOTEXTURAL AND MINERALOGICAL CHANGES WITH STRATIGRAPHIC HEIGHT

Significant changes, in the nature of the volcanic rocks over a stratigraphic height of 2 500 m, include the change from massive and layered flows, containing olivine cumulate zones in the lower zone, to pillowed olivine clinopyroxenite flows in the middle zone, to massive and pillowed flows characterized by suspended plagioclase crystals in the upper zone (Fig. 23). The presence of skeletal olivine crystals in olivine clinopyroxenite pillowed flows, and in cumulus olivine-rich zones in layered flows, suggests that olivine crystallized from the lavas that formed the flows of the lower zone. These lavas also crystallized clinopyroxene and plagioclase. The ultramafic nature of the magma source is indicated by the ubiquitous clusters of euhedral chromite crystals. The same observations and conclusions hold for middle zone rocks, although the relative abundance of olivine-rich flows is much less than in the lower zone. The presence of plagioclase as randomly oriented laths, clusters of euhedral crystals, and dispersed skeletal segments in pillowed flows, and as suspended lath-like crystals in massive flows, and the scarcity of olivine, distinguishes rocks of the upper zone. The lava that gave rise to these rocks crystallized plagioclase and clinopyroxene.

The lavas forming the flows of the lower zone were dominantly plagioclase-bearing, olivine clinopyroxenite to olivine melagabbro to plagioclase-bearing wehrlite in normative composition. The lavas giving rise to the flows of the middle zone were similar in normative composition; however, the normative content of olivine appears to have been less. The lavas giving rise to the flows of the upper zone were gabbroic in composition. These lavas were depleted in normative olivine, and substantially enriched in normative plagioclase, compared with the lavas giving rise to the lower and middle zones.

The dramatic change in the nature of the flows, and the interpreted change in the composition of the lava giving rise to the flows of the Upper volcanic formation, indicates derivation of the lavas from a source chamber in which differentiation was taking place. The lavas are, therefore, considered to represent a succession of liquids, derived from a chamber at different times in its evolution. The most prominent chamber is the Fox River Sill, which underlies, and is separated from rocks of the Upper volcanic formation by a few hundred metres of Middle sedimentary formation sandstone and siltstone. The Sill is a layered differentiated intrusion of substantial size, that ranges from dunite to granophyric gabbro in composition. It has been subdivided into structural zones, including a central layered zone. The lower central layered zone consists of the repetitive cycle, dunite-olivine clinopyroxenite. The upper central layered zone is distinguished by the repetitive cycle, peridotite-pyroxenite-gabbro. Individual cycles may represent infusion of new magma into the chamber and the consequent replacement, and flushing out of old magma. Magma removed from the chamber at the end of an individual lower zone cycle would be clinopyroxene-rich, whereas, magma removed from the end of an individual upper zone cycle would have plagioclase on the liquidus. If some of the removed magma reached the surface, it would form lava flows. Thus, the succession of volcanic rocks from primitive to more evolved kindred could be developed by successive magmatic liquids breaching the intrusion roof, and reaching the surface. The concept of the repetition of cyclic units indicating the successive arrivals of fresh magma batches into the chamber of differentiation has been proposed to explain sequences in the Muskox Intrusion (Irvine and Smith, 1967; Irvine, 1980), the Great Dyke (Worst, 1960), and the Bushveld Complex (Wager and Brown, 1968). Irvine and Smith (op. cit.) suggested that the partly crystallized magma, that was replaced by the arrival of a fresh magma batch, reached the surface as volcanic fissure eruptions.

Textures and mineral morphology indicate that many rocks of the Upper volcanic formation crystallized under non-equilibrium conditions. Olivine, clinopyroxene, and plagioclase form skeletal crystals, and occur in a variety of forms that indicate rapid crystallization, and high degrees of supercooling. This is particularly evident in lower and middle zone rocks, where skeletal olivine, and clinopyroxene are abundant, along with dendritic and spherulitic plagioclase and clinopyroxene. Skeletal crystals, and dendritic and spherulitic crystals are much less common in upper zone rocks. This suggests that the amounts of supercooling of lava decreased with stratigraphic height. The abundance of material interpreted to be altered glass in lower and middle zone rocks indicated that quenching of some lava took place.

CLINOPYROXENE

Clinopyroxene, the best preserved and dominant primary phase in the ultramafic, komatiitic basalt and basalt flows, displays a variety of form, and a range of composition. It occurs as extremely fine grained, frond-like or plumose patches, with continuous wavy extinction, or as a complex pattern of patches with a herring bone-like pattern. This variety is common in pillowed flows, and thin (1-2 m) massive olivine clinopyroxenite flows, and in the uppermost part of layered flows. In some of these rocks, slightly more crystalline patches display curving clinopyroxene blades. The development of more crystalline patches gives rise to rocks characterized by subparallel groups of curving, and straight, skeletal laths and blades. The laths and blades are actually disconnected crystals, composed of clinopyroxene skeletal crystal segments, which have bat wing-or M-shapes. Many of these unusual clinopyroxene forms (hollow blades, crystal segments) are megascopically visible, and have a subparallel arrangement. The resulting textures are interpreted to be pyroxene spinifex. The identification of pyroxene spinifex textures in a given flow defines that flow as komatiitic basalt. In the upper part of some layered flows, numerous fundamental skeletal clinopyroxene segments have been perfectly preserved by quenching of the lava immediately after incipient nucleation. The lower cumulus part of some layered flows contains groups of individual, cumulus, skeletal clinopyroxene crystals. These skeletal crystals have modified shapes through crystal growth. Many basal sections display cores that were originally hollow. The clinopyroxene of clinopyroxenite

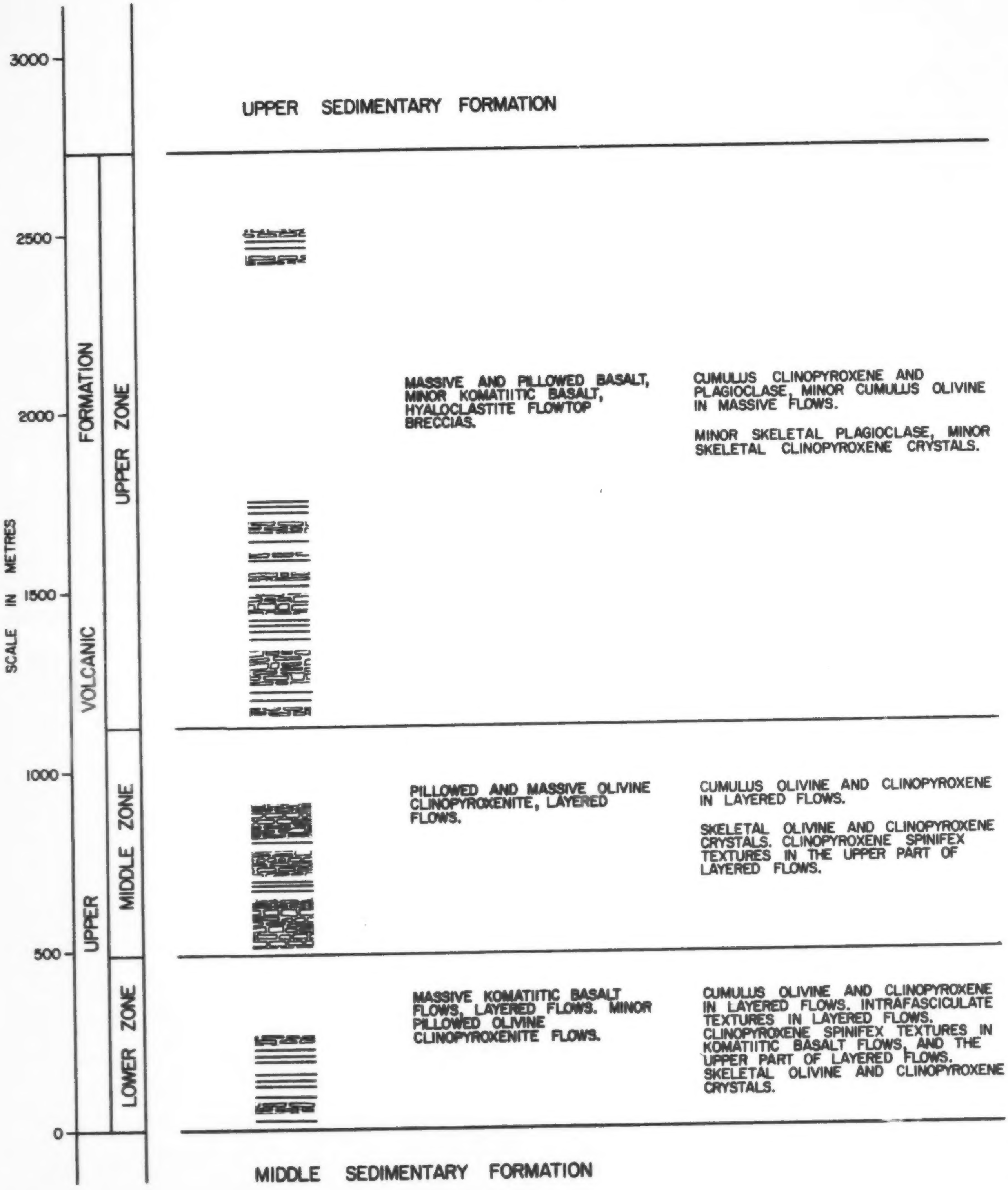

SCALE IN METRES
3000
2500
2000
1500
1000
500
0
UPPER VOLCANIC FORMATION
UPPER ZONE
MIDDLE ZONE
LOWER ZONE
UPPER SEDIMENTARY FORMATION
MASSIVE AND PILLOWED BASALT, MINOR KOMATIITIC BASALT, HYALOCLASTITE FLOWTOP BRECCIAS.
CUMULUS CLINOPYROXENE AND PLAGIOCLASE, MINOR CUMULUS OLIVINE IN MASSIVE FLOWS.
MINOR SKELETAL PLAGIOCLASE, MINOR SKELETAL CLINOPYROXENE CRYSTALS.
PILLOWED AND MASSIVE OLIVINE CLINOPYROXENITE, LAYERED FLOWS.
CUMULUS OLIVINE AND CLINOPYROXENE IN LAYERED FLOWS.
SKELETAL OLIVINE AND CLINOPYROXENE CRYSTALS. CLINOPYROXENE SPINIFEX TEXTURES IN THE UPPER PART OF LAYERED FLOWS.
MASSIVE KOMATIITIC BASALT FLOWS, LAYERED FLOWS. MINOR PILLOWED OLIVINE CLINOPYROXENITE FLOWS.
CUMULUS OLIVINE AND CLINOPYROXENE IN LAYERED FLOWS. INTRAFASCICULATE TEXTURES IN LAYERED FLOWS. CLINOPYROXENE SPINIFEX TEXTURES IN KOMATIITIC BASALT FLOWS, AND THE UPPER PART OF LAYERED FLOWS. SKELETAL OLIVINE AND CLINOPYROXENE CRYSTALS.
MIDDLE SEDIMENTARY FORMATION

FIGURE 23: Lithotextural and mineralogical changes in the Upper volcanic formation

zones of layered flows occurs as well-formed crystals, that commonly display well-developed, hour-glass and sector zones. In some rocks of gabbroic composition, clinopyroxene and plagioclase display what appears to be a complex intergrowth. There are two fundamental relationships. In one, the plagioclase occurs as curving, branching, spherulitic crystals with optically continuous clinopyroxene occupying the originally hollow spaces in the complex plagioclase crystals. In the other, clinopyroxene forms curving, branching spherulitic crystals, and plagioclase occupies the originally hollow spaces in the complex clinopyroxene crystal. In both examples, the result is very complex relationship between clinopyroxene and plagioclase. The clinopyroxenes that occupy plagioclase cores share a common C-axis with the plagioclase (within 5°), and thus, there is a suggestion of an epitaxial relationship between the two minerals. The clinopyroxene of the basalts occurs as yellowish-brown to pinkish-brown, anhedral grains associated with stubby plagioclase laths and prisms. In some basalts, clinopyroxene forms large (up to 3 mm), irregularly shaped grains, poikilitically enclosing numerous plagioclase crystals. The poikilitic grains have colourless to yellowish-brown cores, and brownish rims, and they are often strongly zoned.

The frond-like, plumose variety of clinopyroxene gives an x-ray pattern similar to pigeonite. The colourless skeletal pyroxenes have optical properties of diopside on the basis of birefringence and $\gamma \wedge c$, and the twinned and zoned yellowish-brown, to pinkish-brown clinopyroxene possesses the optical characteristics of augite. This compositional variation of clinopyroxene reflects the change in composition of the lava flows. The frond-like, plumose pigeonite is associated with massive and pillowed olivine clinopyroxenite flows of the lower and middle zone of the volcanic succession. It also occurs in the upper part of layered flow units, which have cumulus clinopyroxene of diopsidic character toward the base of the flow. Brownish augite is associated with upper zone basalt flows. The variation in flow type and clinopyroxene composition is reflected in the chemical variations as will be seen in the section on geochemistry.

The change in shape of clinopyroxene reflects differences in the rate of cooling (Lofgren *et al.*, 1974; Donaldson *et al.*, 1975). Lofgren (in press) has reported that with increasing cooling rates, pyroxenes become elongate, and increasingly skeletal, and at the most rapid cooling rates, the pyroxenes are finely ornamented, feathery or fanspherulite arrays of acicular fibres, often completely interwoven. The unusual pyroxene shapes are associated with mafic and ultramafic flows, a regime in which cooling rates are rapid enough for super cooling, and consequently supersaturation to take place. Hour-glass and sector zoned pyroxenes are also associated with mafic and ultramafic flows, and owe their origin to the conditions extant at the time of crystallization. Unusual pyroxene shapes, and zoned pyroxenes, by contrast, are not found in rocks of the mafic and ultramafic intrusive suite. This observation has been used to distinguish between rocks of intrusive, and extrusive character in drill core where primary volcanic features can be interpreted with difficulty, if at all. In a similar fashion, plagioclase shapes change from tabular crystals, to dendritic crystals, to spherulitic crystals, with increasing degree of supercooling (Lofgren, in press).

Unfortunately, the more highly recrystallized nature of the rocks of the Lower volcanic formation makes critical comparison of the changes in pyroxene morphology, and composition, with that observed in the Upper volcanic formation, difficult. However, original textures are well enough preserved in some rocks to suggest that changes in morphology similar to those described for the Upper volcanic formation also are found in Lower volcanic formation rocks.

METAMORPHISM

LOWER VOLCANIC FORMATION

Chlorite, sphene, epidote and tremolite are the common secondary assemblage minerals of the formation. Albite and quartz are less common, and calcite and muscovite are minor phases. Prehnite and pumpellyite are sporadically distributed throughout the Middle pillowed zone, and rare in rocks of the Upper massive zone, and are absent in rocks of the Lower massive zone.

Tremolite replaces clinopyroxene, and the progressive increase in replacement of clinopyroxene causes an increasing destruction of primary textures. Original basic plagioclase is completely converted to albite ± chlorite ± epidote ± muscovite ± carbonate ± sphene. Within the Middle pillowed zone, original euhedral olivine crystals have been pseudomorphously replaced by chlorite ± quartz ± calcite ± tremolite ± epidote. Grain boundaries between the replaced olivine crystals, and the groundmass are sharp and distinct.

A progressive increase in metamorphic grade toward the base of the formation is marked by an increasing replacement of clinopyroxene by tremolite, and in the near complete replacement of albite by epidote and quartz. These features, and the absence of prehnite and pumpellyite, characterize Lower massive zone rocks.

Rocks of the Middle pillowed zone are less recrystallized than the underlying and overlying lavas. This is reflected in the sporadic distribution of prehnite and pumpellyite, and by a lower abundance of tremolite. The primary textures are, consequently, best preserved in this zone.

Rocks of the Upper massive zone are more highly recrystallized than Middle pillowed zone rocks, and there appears to be an increase in metamorphic grade stratigraphically upward within the zone. Tremolite increases in abundance and prehnite and pumpellyite are rare in the zone. The increasing recrystallization is caused by contact metamorphism of these rocks by the Fox River Sill, which is separated from the volcanic rocks by up to a hundred metres of Middle sedimentary formation sedimentary rocks.

Rocks of the Lower massive and Upper massive zones have recrystallized under conditions close to the albite-actinolite-chlorite zone of low-grade metamorphism (Winkler, 1976), whereas rocks of the Middle pillowed zone were recrystallized under conditions close to the prehnite-pumpellyite-chlorite zone of very low grade metamorphism (Winkler, op. cit.) (Fig. 24).

UPPER VOLCANIC FORMATION

The rocks of the Upper volcanic formation are substantially less recrystallized than their counterparts of the Lower volcanic formation. Chlorite, albite, sphene and quartz are the most common secondary assemblage minerals; tremolite, epidote and carbonate are less common. Prehnite and pumpellyite have a widespread distribution; prehnite being associated with quartz (± chalcedony) ± chlorite ± epidote ± carbonate ± pyrrhotite veinlets. Pumpellyite occurs as regular patches associated with chlorite and epidote, and pseudomorphously replaces skeletal plagioclase crystals. Prehnite and pumpellyite are commonly associated with chlorite in vesicles, and in irregularly-shaped interstitial areas. Quartz ± chlorite ± carbonate ± tremolite, pseudomorphously replaced lantern-or hopper-shaped olivine crystals. The pseudomorphs have perfect olivine morphology, indicating volume for volume replacement. Emerald green celadonite, a variety of glauconite, occurs as very fine grained patches (up to 0.2 mm) and as partial vesicle fillings, associated with chlorite and epidote in some rocks. Nontronite, an iron-rich montmorillonite has been identified in veinlets, where it is associated with plagioclase and celadonite. Neither celadonite nor nontronite is widespread or abundant. Sphene pseudomorphously replaces original, euhedral, trellis-like ilmenite crystals, and albite pseudomorphously replaces original, basic plagioclase.

Tremolite is not abundant in the mafic rocks of the Upper volcanic formation. It occurs as fine grained spears and blades associated with chlorite ± quartz ± carbonate, and as pseudomorphous replacements of lantern- or hopper-shaped olivine in pillowed and massive clinopyroxene-rich flows. It also occurs in veinlets associated with pyrrhotite and carbonate.

The assemblage chlorite ± carbonate ± serpentine ± talc ± tremolite is common in olivine-rich ultramafic rocks of the volcanic sequence. Talc ± tremolite ± chlorite is a common assemblage, pseudomorphously replacing olivine, and tremolite occurs as a ragged overgrowth on otherwise well-preserved clinopyroxene in these rocks. A brownish, very fine grained material, interpreted to be an alteration of an original glass in some ultramafic rocks, may be amphibole.

Muscovite, as very fine grained laths or blades, or as fine grained felted aggregates, replaces plagioclase.

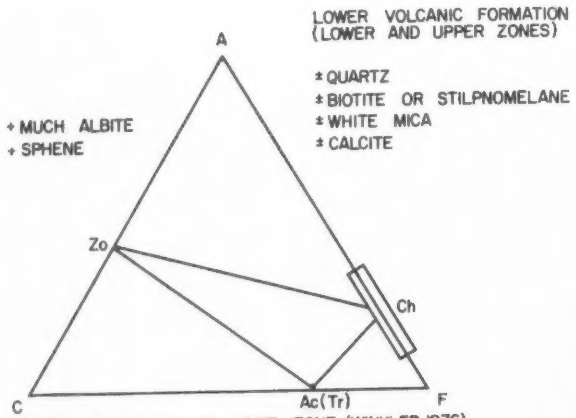
Diopside and pigeonite have been identified, and the generally well-preserved clinopyroxene outlines, and gives emphasis to the primary texture. Skeletal crystals of basic plagioclase (labradorite/bytownite) are preserved in some upper zone rocks.

The widespread distribution of prehnite and pumpellyite, and the common secondary assemblage of chlorite, tremolite, albite, sphene and quartz are typical of the pumpellyite-prehnite-quartz facies of very low grade metamorphism (Winkler, 1976) (Fig. 24). The lack of albitization of basic plagioclase in some rocks, and the sporadic distribution of celadonite (glauconite) and nontronite (montmorillonite) indicates that the reconstitution of basic plagioclase, and clay minerals by very low grade metamorphism was not complete.

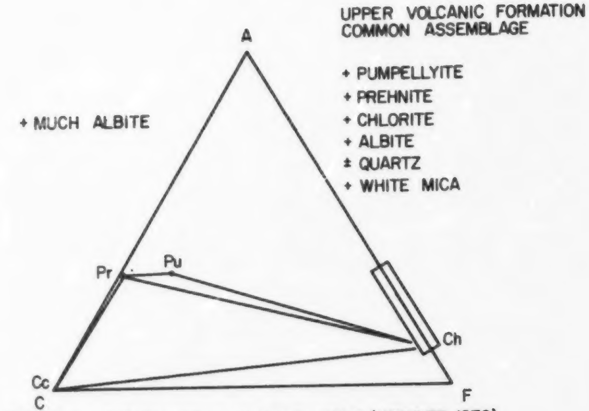
As Winkler (op. cit.) has pointed out, a number of reactions may produce the association pumpellyite ± prehnite ± chlorite, and this assemblage by itself if not a precise indicator of metamorphic conditions. Other minerals diagnostic of very low grade metamorphism (laumontite, wairakite, lawsonite, glaucophane) have not been observed in Upper volcanic formation rocks.

SUMMARY

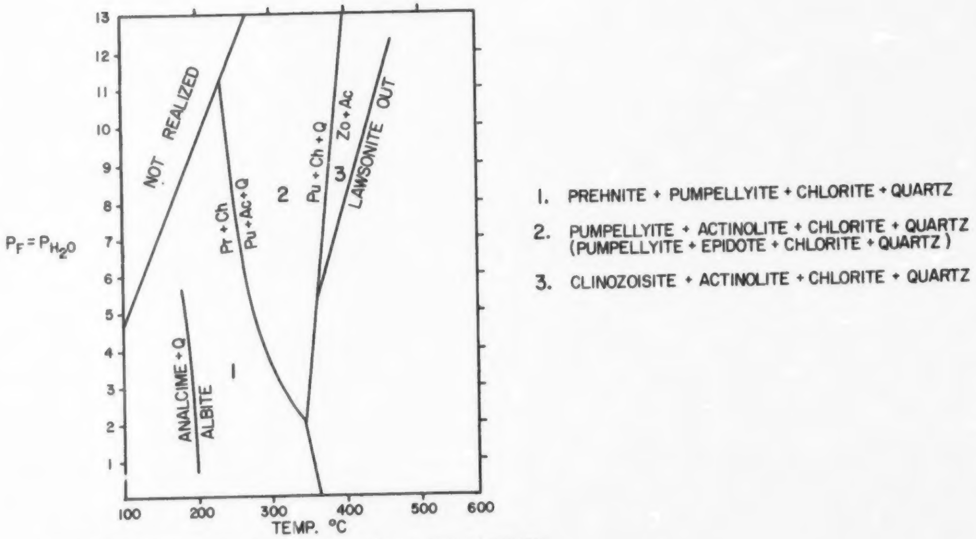
There is a distinct trend toward less recrystallized rocks with stratigraphic height in the volcanic formations. Since the secondary assemblage chlorite, tremolite, albite, sphene, quartz, epidote and carbonate is common to mafic volcanic rocks of the Lower and Upper formations, the presence of prehnite and pumpellyite in the rocks of the Upper formation, indicates a lower grade of metamorphism. Conversely, an increase in recrystallization downward is indicated by increasing replacement of clinopyroxene by tremolite, and absence of prehnite and pumpellyite toward the base of the Lower volcanic formation.


LOWER VOLCANIC FORMATION
(LOWER AND UPPER ZONES)
± QUARTZ
± BIOTITE OR STILPNOMELANE
± WHITE MICA
± CALCITE
+ MUCH ALBITE
+ SPHENE
A
Zo
Ch
C
Ac(Tr)
F

ALBITE - ACTINOLITE - CHLORITE ZONE (WINKLER,1976)


UPPER VOLCANIC FORMATION
COMMON ASSEMBLAGE
+ PUMPELLYITE
+ PREHNITE
+ CHLORITE
+ ALBITE
± QUARTZ
+ WHITE MICA
+ MUCH ALBITE
A
Pr
Pu
Ch
Cc
C
F

PREHNITE - PUMPELLYITE - CHLORITE ZONE (WINKLER,1976)



PHASE RELATIONS IN VERY LOW GRADE METAMORPHISM,
(SIMPLIFIED FROM WINKLER, 1976).

FIGURE 24: Representation of characteristic metamorphic minerals and pertinent reactions

GEOCHEMISTRY

TERMINOLOGY

Viljoen and Viljoen (1969), proposed the term komatiite to define a new class of mafic and ultramafic volcanic rocks, and suggested that komatiites be distinguished as peridotitic komatiite (MgO > 20%), and basaltic komatiite (MgO, 9-20%). Arndt (1975), and Arndt *et al.* (1977) proposed that komatiites be divided into peridotitic komatiites (MgO > 20%), pyroxenitic komatiites (MgO, 12-20%), and basaltic komatiites (MgO, 8-12%). More recently, the term komatiite has been defined as an ultramafic volcanic rock, and a value of 18% MgO has been suggested for separating komatiite from basalt (Arndt and Brooks, 1980). Under this proposal, the term komatiite would have the rank of a rock type like basalt and andesite. In this report, the term komatiite is used in accordance with the Penrose conference proposal (Arndt and Brooks, op. cit.), and the term komatiitic basalt is used to define rocks that have the unusual textures, and unique chemical characteristics of komatiites, but which have MgO contents less than 18 percent. As used herein, the term komatiitic basalt is compatible with the term basaltic komatiite as defined by Viljoen and Viljoen (op. cit.), used by Nisbet *et al.* (1977), and with the terms basaltic komatiite and pyroxenitic komatiite as proposed by Arndt (op. cit.), and Arndt *et al.* (op. cit.).

CHEMICAL VARIATION

Whole rock chemical analyses have been performed on 38 mafic volcanic rocks, 13 from the Lower volcanic formation, and 25 from the Upper volcanic formation. The analyses are grouped according to pillowed, layered, and simple massive flows, and are organized according to their relative stratigraphic position (Table 2). The pillowed flows are thought to represent near liquid compositions, despite the abundance of fine grained euhedral olivine crystals. Many of the olivine crystals are skeletal, and many of those that are solid have skeletal overgrowths. These features, and the presence of hopper and ornamental chain-like crystals, indicate that the olivine crystallized from liquid. Thus, the pillowed flows are considered to have crystallized from lavas containing few phenocrysts. Rocks, possibly enriched in phenocrysts, are found in the cumulus parts of layered flows, where cumulus olivine and clinopyroxene occur. Examples of skeletal olivine and clinopyroxene among the cumulus crystals suggest the possibility that these minerals crystallized from the liquid during and/or after eruption. Simple massive flows appear for the most part to have been phenocryst-free. The rocks display a considerable range in composition, pillowed flows ranging from 6 to nearly 16 percent MgO (hydrous) and an individual layered flow ranging from 9 to 24 percent MgO (hydrous). The ultramafic character of some flows is reflected in their relatively high MgO contents.

Fox River mafic volcanic rocks display tholeiitic characteristics in being hypersthene and quartz normative (Table 2), and in displaying a trend toward iron enrichment in the standard AFM diagram (Fig. 25a). The scatter on this diagram probably represents alteration that affected alkali abundances. The rocks display komatiitic characteristics on the other chemical variation diagrams. The effect of olivine control on the rock series can be seen on the CaO-MgO-Al_2O_3 diagram (Fig. 25b), where the plotted points trend away from the MgO corner toward the CaO-Al_2O_3 join. The komatiitic character of the rocks is clearly seen on the Jensen cation diagram (Fig. 25c), where the points form a coherent series across the komatiitic basalt into the tholeiite field. A slight trend toward iron enrichment can be seen. The komatiitic character of these rocks can also be seen on the Al_2O_3 vs FeO/FeO + MgO diagram (Fig. 26a), where all but two of the points lie in the komatiitic field. The line separating komatiitic and tholeiitic fields on the Al_2O_3 vs FeO/FeO + MgO diagram is used by Naldrett and Cabri (1976) to separate Munro Township komatiites and tholeiites. This line effectively separates Fox River komatiites and tholeiites. The serial nature of the points is also displayed on this diagram, as well as on the TiO_2 vs MgO diagram (Fig. 26b), where the low TiO_2 content of the rocks can be seen. The chemically contiguous nature of the volcanic suite is well displayed on the NiO vs MgO and Cr_2O_3 vs MgO diagrams (Figs. 26c and 26d), where a direct relationship exists between MgO and NiO and Cr_2O_3 abundances. The spread in NiO and Cr_2O_3 reflects the relative abundances in the rocks of Ni-sulphides, and chromite, respectively.

The Fox River mafic volcanic rocks have the chemical characteristics of komatiitic suites. They form a serial or coherent series that form trends on the chemical variation diagrams that are due to olivine fractionation. The trends extend unbroken from komatiitic basalt fields to tholeiitic basalt fields, indicating that the tholeiites are part of the suite. The chemical data supports the conclusions based on petrologic considerations that the flows form a coherent, petrogenetically related suite.

RELATIONSHIPS BETWEEN LAVAS AND DIFFERENTIATED INTRUSIONS

There is a progressive decrease in MgO/MgO + FeO with stratigraphic height in Lower volcanic formation and Upper volcanic formation pillowed flows (Figs. 27a and 27b). Pillowed flows only have been used as these rocks are considered to represent close approximations to liquid compositions. Thus, successive lavas became more iron-rich with time. This observation reinforces the conclusion, based on petrologic considerations, that the lavas were derived from a source chamber in which differentiation was taking place. The Lower and Upper volcanic formations are underlain by differentiated intrusions that are considered to be the obvious choices for source chambers. Fractional crystallization of magmatic liquids in the chambers would give rise to more highly evolved liquids with time. The more highly evolved nature of the liquids would be manifest by the liquid becoming more iron-rich, and by an increasing abundance of incompatible elements, such as TiO_2, with time. Features such as these have been recognized in the volcanic formations, and are particularly well-exemplified by a progressive decrease in MgO/MgO + FeO (Figs. 27a and b) and by a progressive increase in TiO_2, with stratigraphic height (Figs. 27c and d).

The nature of the relationship between the differentiated intrusions and the lavas is illustrated in Figure 28, where the fields for Fox River mafic volcanic rocks, and the Fox River Sill are outlined. In some of the diagrams, the Fox River Sill has been subdivided into its four lithostructural parts. The Fox River Sill data extend the trends of the mafic volcanic rocks to the Mg-rich parts of the diagrams. In the CaO-MgO-Al_2O_3 diagram (Fig. 28b), three elliptical fields occur near the mid-point of the CaO-MgO join. These fields represent clinopyroxenites from three different parts of the Sill. Fox River Sill dunites and peridotites plot at or near the MgO corner, and Sill gabbros overlap with basalts of the lavas. The evidence suggests that the Sill has acted as a subvolcanic chamber through which magmatic liquids undergoing fractional crystallization have passed, and that succes-

TABLE 2
CHEMICAL ANALYSES AND CIPW NORMATIVE MINERALOGY, FOX RIVER MAFIC VOLCANIC ROCKS.

LOWER VOLCANIC FORMATION

	Middle Pillowed Zone											Upper Massive Zone	
	Pillowed Flows							Layered Flow				Massive Flows	
	220-2b	98-1	99-1	224	266	217	222	98-2	98-3	98-4	98-5	215-2	254-1
SiO_2	48.45	43.35	50.20	50.65	48.10	50.00	47.85	51.50	50.20	49.80	47.65	54.00	48.15
Al_2O_3	11.70	12.80	12.45	14.15	14.70	14.15	13.75	12.80	13.83	8.41	11.52	13.47	13.30
Fe_2O_3	2.03	2.24	2.17	2.02	2.83	2.84	1.91	1.34	1.76	1.45	1.19	2.93	1.80
FeO	8.36	9.36	7.10	8.34	8.07	7.60	9.90	8.10	8.12	8.30	8.22	8.98	12.97
CaO	10.90	14.10	12.20	9.93	10.85	12.40	10.42	8.27	9.08	10.20	10.90	8.34	6.06
MgO	11.90	11.00	9.16	8.27	7.90	7.33	9.30	9.04	8.92	15.50	13.20	4.82	6.83
Na_2O	1.72	.15	2.23	1.50	1.47	1.40	2.03	3.58	3.13	1.29	1.63	2.33	3.58
K_2O	0.06	.28	.11	.31	.13	.07	.19	.18	.34	.12	.10	.21	.68
TiO_2	0.74	.83	.80	.77	.89	.85	.87	.81	.86	.66	.64	1.62	1.88
P_2O_5	.08	.07	.06	.08	.09	.10	.08	.07	.08	.05	.06	.25	.20
MnO	.18	.20	.14	.20	.18	.18	.21	.15	.15	.17	.17	.16	.22
NiO	.05	.03	.04	.015	.03	.015	.015	.02	.01	.05	.05	.01	.005
Cr_2O_3	.16	.10	.12	.05	.05	.06	.05	.09	.05	.18	.15	.01	.02
H_2O	3.48	4.64	2.53	3.26	3.76	2.52	3.29	3.22	3.43	3.83	4.23	2.86	3.78
S	.01	.14	.10	.09	.05	.07	.01	.13	.01	.01	.05	.44	.10
CO_2	.15	.93	.53	.24	.88	.22	.08	.48	.07	.14	.25	.02	.03
-O/S	—	.06	.04	.04	.02	.03	—	.05	—	—	.02	.18	.04
TOTAL	99.97	100.16	99.90	99.84	99.96	99.78	99.96	99.73	100.04	100.16	99.99	100.27	99.57

UPPER VOLCANIC FORMATION

	Lower Zone						Middle Zone								
	Layered Flow						Pillowed Flows						Layered Flow		
	57-2	242-2	57-4	242	57-6	57-8	57-9	240	87-1	89-1	77-2	93-1	77-4	77-5	77-6
SiO_2	51.95	48.90	46.85	47.10	41.65	43.25	45.70	46.60	47.10	48.80	46.50	46.30	51.20	46.10	44.25
Al_2O_3	11.55	13.15	11.79	10.65	10.33	6.40	12.35	12.20	9.59	10.81	10.11	10.22	12.06	8.16	8.31
Fe_2O_3	1.36	1.67	1.49	1.19	1.40	1.81	2.81	4.42	1.81	2.04	1.50	1.82	1.62	1.79	1.43
FeO	8.89	8.93	10.26	8.85	10.79	8.81	8.73	7.06	8.50	7.66	9.44	8.54	7.29	8.54	9.15
CaO	10.30	8.60	12.30	10.05	8.75	6.17	13.30	15.90	12.50	9.79	10.04	11.10	9.24	10.70	8.29
MgO	9.45	9.80	10.65	15.25	19.70	24.40	10.90	9.59	14.80	13.80	15.90	15.00	11.50	19.00	21.40
Na_2O	1.71	2.70	.92	1.27	.09	.01	.81	.98	.73	1.70	1.13	1.13	2.75	.16	.08
K_2O	.04	.07	.04	NIL	NIL	.01	.05	.06	.17	.14	.10	.17	.18	.03	.01
TiO_2	.72	.75	.76	.63	.64	.46	.84	.78	.63	.64	.66	.63	.73	.59	.51
P_2O_5	.11	.07	.12	.05	.08	.06	.08	.08	.49	.06	.07	.06	.08	.06	.05
MnO	.16	.15	.19	.20	.26	.16	.19	.17	.19	.16	.19	.17	.15	.18	.15
NiO	.02	.015	.03	.06	.05	.17	.05	.03	.06	.07	.08	.07	.05	.09	.12
Cr_2O_3	.13	.08	.15	.20	.15	.53	.19	.15	.19	.22	.27	.21	.22	.33	.41
H_2O	3.48	3.58	3.94	4.55	6.31	7.87	3.02	2.14	3.27	3.80	4.09	4.01	2.91	4.90	6.27
S	.02	.12	.06	.003	NIL	.06	.04	.05	NIL	.02	.01	.03	.01	NIL	NIL
CO_2	.04	—	.05	.14	.03	.05	.65	.10	.05	.08	.03	.54	.01	.10	.02
-O/S	.01	—	.02	—	—	.02	.02	.02	—	.01	—	.01	—	—	—
TOTAL	99.92	98.59	99.56	100.19	100.23	100.20	99.69	100.29	100.08	99.78	100.12	99.99	100.00	100.73	100.45

	Upper Zone									
	Pillowed Flows				Massive Flows					
	107-2	105-2	101	239	250-1A	250-3	250-4C	250-4G	250-4J	248-2
SiO_2	49.95	48.20	49.75	50.65	50.60	49.55	49.85	50.60	50.60	57.30
Al_2O_3	14.40	14.79	13.75	13.60	13.83	14.14	12.54	13.86	14.08	15.85
Fe_2O_3	2.31	2.47	1.89	1.83	2.45	3.00	1.50	2.91	1.34	1.03
FeO	7.74	8.10	9.30	9.46	7.42	7.26	8.94	6.45	8.57	5.54
CaO	11.80	11.60	11.40	8.95	11.70	12.50	9.60	12.60	10.40	4.75
MgO	7.80	8.60	7.79	6.00	8.14	7.73	9.80	8.09	8.25	6.37
Na_2O	1.53	1.36	1.93	2.75	1.55	1.35	1.93	1.08	2.52	4.07
K_2O	.26	.21	.12	.28	.05	.11	.04	.37	.08	.10
TiO_2	.81	.85	.90	1.84	.76	.72	.88	.68	.81	.96
P_2O_5	.06	.07	.08	.18	.08	.08	.08	.08	.08	.09
MnO	.18	.19	.21	.21	.18	.18	.14	.18	.19	.09
NiO	.02	.01	.01	.01	.02	.015	.02	.02	.015	.02
Cr_2O_3	.04	.04	.04	.02	.06	.06	.06	.06	.06	.06
H_2O	2.77	3.26	2.22	3.28	2.68	2.92	4.15	2.79	2.63	3.39
S	.05	.01	.02	.03	.02	.02	.03	.03	.02	.02
CO_2	.37	.07	.88	1.27	.05	.27	NIL	.08	.16	.14
-O/S	.02	—	.01	.01	.01	.01	.01	.01	.01	.01
TOTAL	100.07	99.83	100.28	100.35	99.58	99.90	99.55	99.87	99.80	99.77

CIPW NORMATIVE MINERALOGY

	220-2b	98-1	99-1	224	266	217	222	98-2	98-3	98-4	98-5	215-2	254-1
Q	—	—	.56	5.31	3.44	5.68	—	—	—	—	—	12.92	—
C	—	—	—	—	—	—	—	—	—	—	—	—	—
Or	.37	1.77	.67	1.92	.62	.43	1.17	1.10	2.07	.73	.61	1.31	4.24
Ab	15.95	1.43	20.64	14.11	14.01	13.15	18.93	33.05	28.88	11.87	15.11	22.02	33.86
An	24.82	35.64	24.38	32.45	35.17	33.61	28.93	18.85	23.32	17.23	24.60	27.04	19.19
Di	18.44	22.17	22.67	10.18	11.90	16.80	12.85	12.92	12.66	21.85	18.93	6.94	4.76
He	5.95	8.58	7.44	4.72	5.16	7.26	6.53	5.38	5.30	5.61	5.74	4.91	4.13
En	18.92	11.14	14.74	18.83	17.20	12.77	13.47	14.32	11.78	27.87	14.69	10.54	8.22
Fs	6.11	4.31	4.84	8.75	7.48	5.52	6.84	5.96	4.93	7.15	4.45	7.46	7.14
Fo	4.34	7.60	—	—	—	—	5.08	3.66	5.40	3.81	10.10	—	6.95
Fa	1.40	2.94	—	—	—	—	2.58	1.52	2.26	.98	3.06	—	6.03
Mt	2.19	2.50	2.34	2.21	3.14	3.11	2.07	1.44	1.89	1.55	1.29	3.23	1.98
Il	1.07	1.23	1.15	1.12	1.32	1.24	1.26	1.16	1.23	.94	.92	2.38	2.76
Cr	.19	.12	.14	.06	.06	.07	.06	.10	.06	.21	.17	.01	.02
Ap	.17	.16	.13	.16	.20	.22	.17	.15	.17	.11	.13	.55	.44
Py	.03	.39	.27	.14	.08	.11	.03	.35	.03	.03	.13	.71	.27

	57-2	242-2	57-4	242	57-6	57-8	57-9	240	87-1	89-1	77-2	93-1	77-4	77-5	77-6
Q	5.16	—	—			—	—	—	—	—	—	—	—	—	—
C	—					—	—	—	—	—	—	—	—	—	—
Or	.25	.43	.25	—	—	.06	.31	.37	1.03	.85	.61	1.04	1.08	.18	.06
Ab	16.03	25.33	8.71	11.75	.84	.09	7.63	9.09	6.73	15.70	10.41	10.49	25.08	1.47	.74
An	24.77	24.62	29.45	24.09	28.92	18.11	31.39	29.66	22.98	22.08	22.80	23.08	20.35	22.00	22.99
Di	15.30	10.93	18.54	16.76	9.84	9.14	22.16	32.67	23.50	17.59	17.29	21.16	15.97	21.15	12.65
He	6.96	4.67	8.73	4.82	2.73	1.55	7.67	8.35	6.40	4.41	4.99	5.62	4.58	4.47	2.63
En	19.58	17.05	18.97	19.30	16.52	33.76	15.67	9.78	20.02	23.14	17.39	14.55	19.42	26.70	28.04
Fs	8.91	7.29	8.93	5.55	4.59	5.71	5.42	2.50	5.46	5.80	5.01	3.87	5.57	5.64	5.82
Fo	—	4.32	2.08	11.77	26.37	23.86	3.61	.92	7.62	5.44	14.25	13.27	3.63	12.37	19.92
Fa	—	1.85	.98	3.38	7.32	4.03	1.25	.24	2.08	1.36	4.11	3.53	1.04	2.61	4.14
Mt	1.48	1.82	1.64	1.28	1.52	1.97	3.08	4.77	1.94	2.19	1.61	1.97	1.72	1.92	1.54
Il	1.05	1.09	1.12	.90	.93	.67	1.23	1.12	.90	.92	.94	.91	1.03	.84	.73
Cr	.15	.09	.18	.23	.17	.62	.22	.17	.22	.25	.31	.24	.25	.38	.47
Ap	.24	.15	.27	.11	.17	.13	.18	.17	1.05	.13	.15	.13	.17	.13	.11
Py	.05	.33	.11			.11	.11	.13	—	.05	.03	.08	.03	—	—

	107-2	105-2	101	239	250-1A	250-3	250-4C	250-4G	250-4J	248-2
Q	3.81	1.69	1.61	4.07	5.21	4.87	1.83	6.46	.33	9.79
C	—	—	—	—	—	—	—	—	—	.70
Or	1.60	1.30	.74	1.75	.31	.68	.24	2.28	.49	.61
Ab	14.31	12.76	18.01	26.14	14.51	12.70	18.19	10.12	23.33	37.59
An	32.98	35.15	29.63	25.35	31.94	33.74	26.70	33.27	27.72	23.64
Di	15.36	13.85	14.66	9.79	16.05	17.65	12.70	19.01	13.30	—
He	6.72	5.76	8.24	6.55	6.38	6.90	5.49	6.13	6.67	—
En	14.75	17.88	15.02	12.64	15.40	13.53	22.05	13.80	16.84	18.09
Fs	6.45	7.44	8.44	8.46	6.12	5.29	9.54	4.45	8.44	6.78
Fo	—	—	—	—	—	—	—	—	—	—
Fa	—	—	—	—	—	—	—	—	—	—
Mt	2.52	2.70	2.05	2.03	2.67	3.29	1.65	3.17	1.45	1.11
Il	1.18	1.24	1.30	2.71	1.10	1.05	1.29	.99	1.16	1.38
Cr	.05	.05	.05	.02	.07	.07	.07	.07	.07	.07
Ap	.13	.15	.17	.40	.18	.18	.18	.18	.17	.19
Py	.14	.03	.05	.08	.03	.03	.06	.05	.03	.03

LOWER VOLCANIC FORMATION

Middle Pillowed Zone

Pillowed flows

220-2b	Rock originally composed of skeletal clinopyroxene segments in a highly altered groundmass. An original clinopyroxenite. Fox River south 3 section
98-1	Rock originally composed of euhedral olivine in a matrix of frond-like, plumose clinopyroxene. An original olivine clinopyroxenite. Great Falls section, Fox River
99-1	Rock as 98-1. Great Falls section. Fox River
224	Rock composed of blade-like clinopyroxene and lath-like plagioclase crystals. An original gabbro. Fox River south 3 section
266	Rock originally composed of lath-like plagioclase crystals and irregularly-shaped clinopyroxene crystals. An original gabbro. Great Falls section. Fox River
217	Rock as 266 Great Falls section. Fox River
222	Rock originally composed of euhedral plagioclase crystals in a groundmass of fine-grained, radially disposed fibre-like clinopyroxene crystals. An original plagioclase-bearing clinopyroxenite to gabbro. Fox River south 3 section

Layered flow

98-2 98-3 98-4 98-5	Sequence of samples across layered flow. Great Falls section, Fox River.
98-2	Flow top. Rock originally composed of dispersed skeletal clinopyroxene segments and olivine in a groundmass of frond-like plumose clinopyroxene. An original olivine clinopyroxenite
98-3	Upper, columnar jointed part of flow. Rock originally composed of suspended skeletal clinopyroxene segments in a groundmass of fine-grained plagioclase and clinopyroxene. An original plagioclase-bearing clinopyroxenite
98-4	Upper part of cumulus zone. Rock originally composed of suspended, equidimensional clinopyroxene and olivine crystals in a groundmass distinguished by intrafasciculate-textured plagioclase and clinopyroxene. An original plagioclase-bearing olivine clinopyroxenite
98-5	Lower part of cumulus zone. Rock as 98-4

Upper Massive Zone

Massive flows

215-2	Rock originally composed of lath-like plagioclase crystals and stubby, prismatic clinopyroxene crystals. An original gabbro. Great Falls section. Fox River
254-1	Rock originally composed of lath-like plagioclase and irregularly-shaped clinopyroxene crystals. An original gabbro. Great Falls section. Fox River

UPPER VOLCANIC FORMATION

Lower Zone

Layered flow

57-2 242-2 57-4 242 57-6 57-8	Sequence of samples across layered flow. Fox River north 1 section
57-2	Vesiculated flow top. Rock composed of fine-grained skeletal clinopyroxene in a fine-grained matrix of acicular plagioclase. An original gabbro
242-2	Upper part of flow. Rock composed of fine-grained, irregularly-shaped, blade-like clinopyroxene crystals in a matrix of fine-grained, radiating, acicular to fibre-like plagioclase crystals. Rock is characterized by the presence of finely dispersed graphite. An original gabbro
57-4	Upper part of flow. Rock composed of skeletal clinopyroxene segments in a matrix of radiating acicular or fibre-like plagioclase crystals. An original gabbro
242	Transition between upper and lower part of flow. Rock originally composed of suspended olivine and skeletal clinopyroxene in a matrix of intrafasciculate-textured plagioclase and clinopyroxene coarse clinopyroxene fronds and plumes and altered glass. An original olivine clinopyroxenite
57-6	Transition between upper and lower part of flow. Rock originally composed of suspended olivine and skeletal clinopyroxene in a groundmass of intrafasciculate-textured plagioclase and clinopyroxene. An original olivine melagabbro
57-8	Lower cumulus part of flow. Rock originally composed of cumulus olivine and minor cumulus clinopyroxene in a fine-grained matrix of intrafasciculate-textured plagioclase and clinopyroxene. Olivine content is estimated to range between 50 and 60 percent. An original olivine melagabbro to olivine-poor wehrlite

Middle Zone

Pillowed flows

57-9	Rock originally composed of clusters of fine-grained euhedral olivine and hopper olivine in a groundmass of frond-like, plumose clinopyroxene and randomly oriented skeletal clinopyroxene segments. An original olivine clinopyroxenite. Fox River north 2 section
240	Rock originally composed of clusters of euhedral olivine and elongate, randomly disposed ornamental chain-like olivine crystals in a groundmass of frond-like, plumose clinopyroxene. An original olivine clinopyroxenite. Fox River north 2 section
87-1	Rock originally composed of clusters of euhedral olivine crystals in a groundmass of frond-like, plumose and herring-bone-like pyroxene. An original olivine clinopyroxenite. Otter Falls section, Stupart River
89-1	Rock as 87-1. Otter Falls section. Stupart River
77-2	Rock originally composed of clusters of euhedral olivine crystals and randomly disposed ornamental chain-like olivine crystals in a groundmass of plumose and herringbone-like clinopyroxene. An original olivine clinopyroxenite. Otter Falls section. Stupart River
93-1	Rock as 87-1. Otter Falls section. Stupart River

Layered flow

77-4 77-5 77-6	Sequence of samples across layered flow. Otter Falls section, Stupart River
77-4	Flow top. Rock originally composed of clusters of euhedral olivine, hopper olivine and ornamental chain-like olivine crystals in a groundmass of frond-like, plumose clinopyroxene. The matrix clinopyroxene is slightly coarser than that of pillowed olivine clinopyroxenites previously described. An original olivine clinopyroxenite
77-5	Upper columnar jointed part of flow. Rock originally composed of suspended olivine crystals and skeletal clinopyroxene segments in a glassy groundmass. An original olivine melagabbro
77-6	Lower cumulus part of flow. Rock originally composed of cumulus olivine and clinopyroxene crystals in a glassy matrix. An original olivine melagabbro to olivine-poor wehrlite

Upper Zone

Pillowed flows

107-2	Rock composed of blade-like clinopyroxene and skeletal clinopyroxene segments and randomly disposed plagioclase laths. An original gabbro. Jackfish Falls section. Stupart River
105-2	Rock composed of blade-like clinopyroxene and skeletal clinopyroxene segments and randomly disposed plagioclase laths. Some dendritic to spherulitic clinopyroxene crystals in intrafasciculate textural relationship with plagioclase. An original gabbro. Jackfish Falls section. Stupart River.
101	Rock originally composed of clusters of euhedral plagioclase crystals and dispersed skeletal plagioclase segments in a groundmass of radiating, fibre-like clinopyroxene crystals. An original gabbro. Jackfish Falls section. Stupart River.
239	Rock is vesicular and is composed of randomly oriented lath plagioclase and irregularly-shaped clinopyroxene crystals. An original gabbro. Fox River north 3 section

Massive flows

250-1A	Rock composed of blade-like and ornamental chain-like clinopyroxene crystals, and lath-like plagioclase crystals. An original gabbro. Jackfish Falls section, Stupart River
250-3	Rock composed of blade-like clinopyroxene crystals and lath-like plagioclase crystals. Some dendritic to spherulitic clinopyroxene crystals in the groundmass. An original gabbro. Jackfish Falls section, Stupart River.
250-4C 250-4G 250-4J	A sequence of samples across a simple massive flow. Jackfish Falls section, Stupart River.
250-4C	Lower part of flow. Rock composed of randomly disposed plagioclase laths and irregularly-shaped clinopyroxene as individual crystals and crystal aggregates. An original gabbro.
250-4G	Middle part of flow. Rock composed of large irregularly-shaped, poikilitic clinopyroxene crystals and randomly disposed plagioclase laths. The groundmass contains finer-grained non-poikilitic clinopyroxene crystals. An original gabbro.
250-4J	Upper part of flow. Rock composed of randomly disposed skeletal plagioclase laths and clusters of euhedral plagioclase crystals in a groundmass of coarse plumose, frond-like clinopyroxene. An original gabbro.
248-2	Hyaloclastite, flow top breccia. Jackfish Falls section, Stupart River.

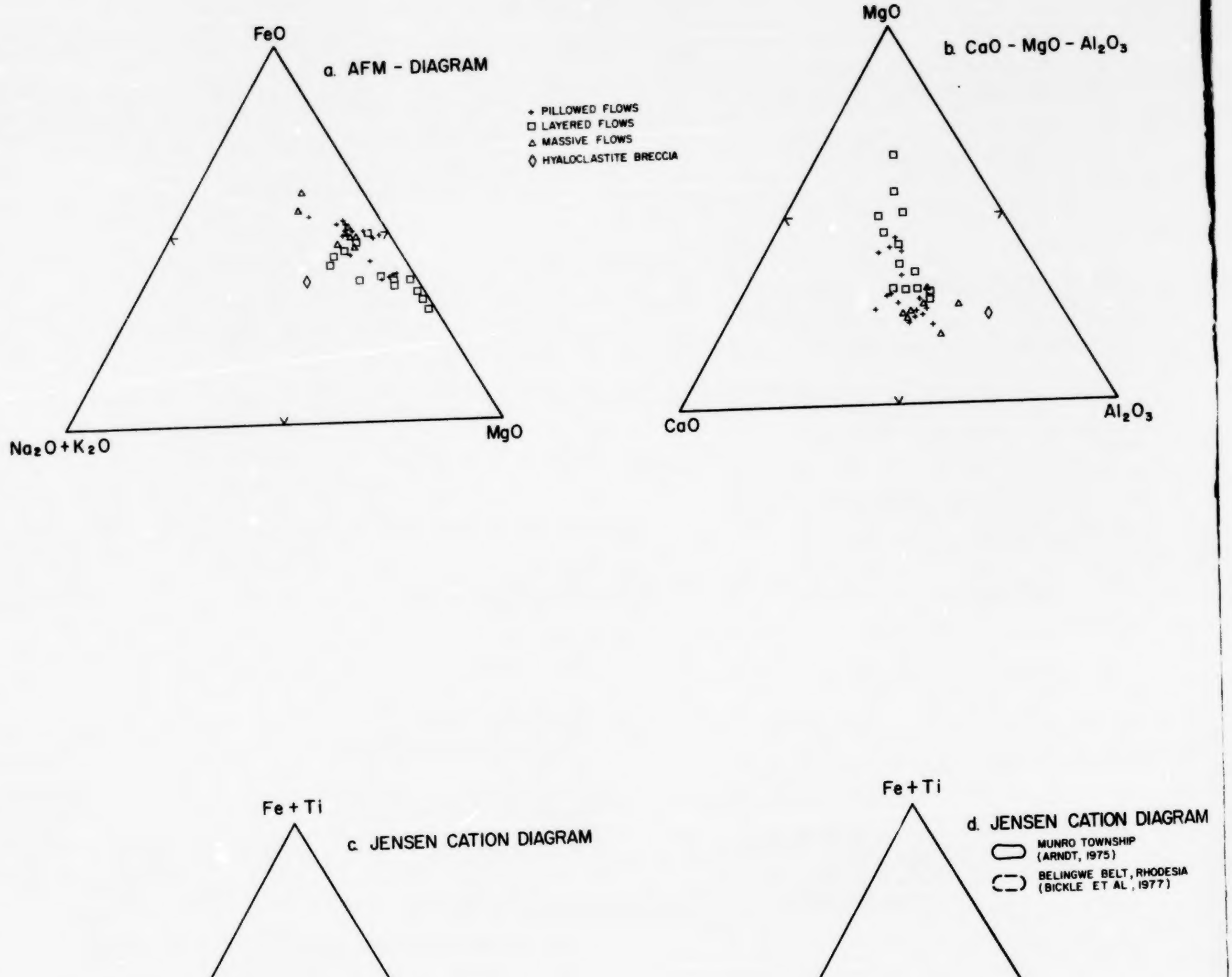
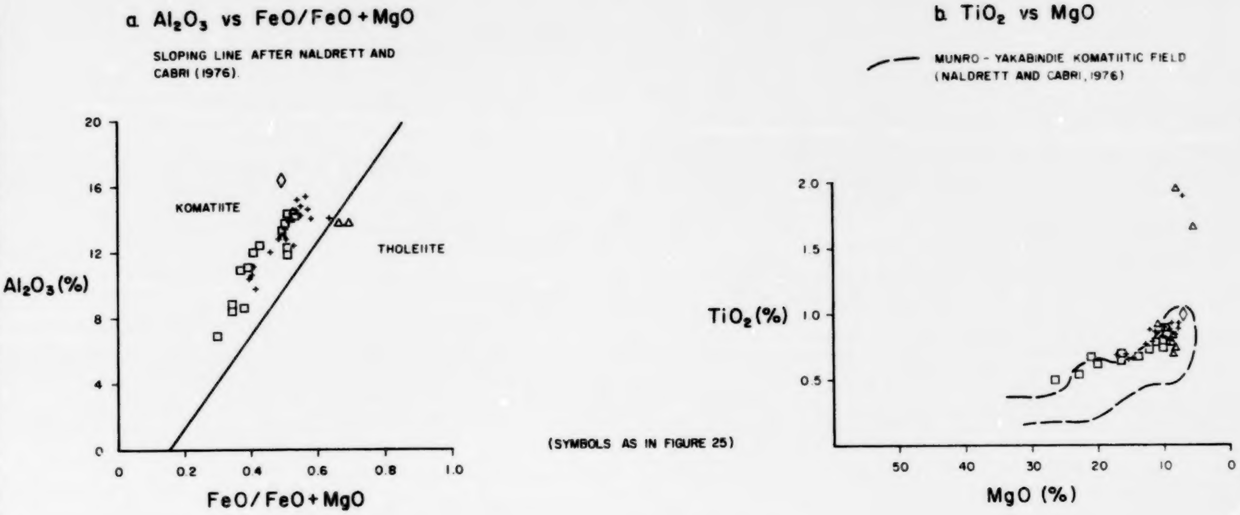
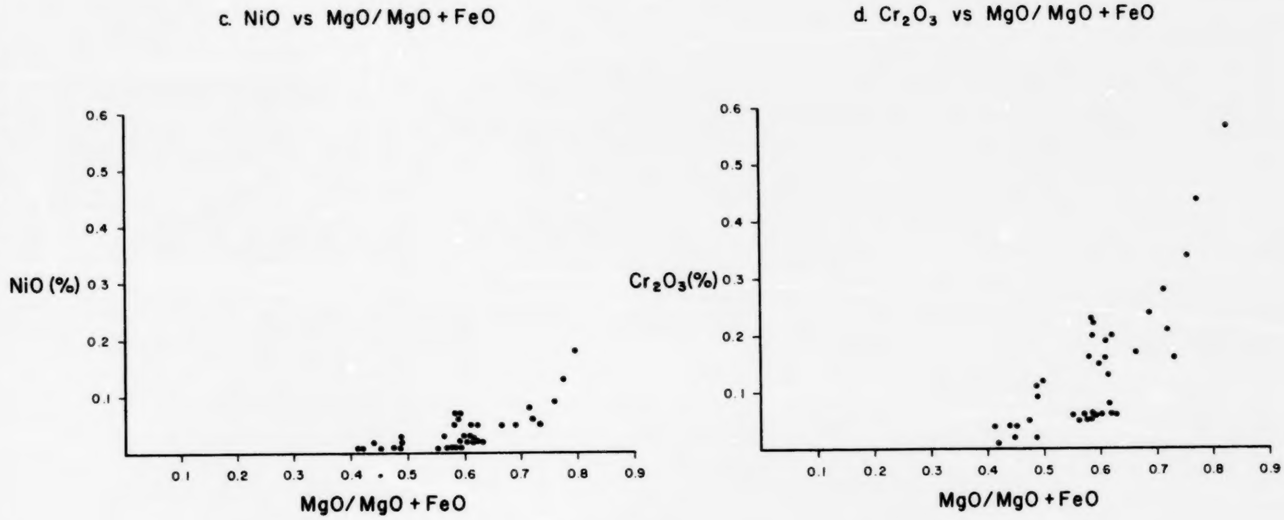


FIGURE 25: Chemical variation of Fox River volcanic rocks — ternary variation diagrams



a. Al_2O_3 vs FeO/FeO + MgO

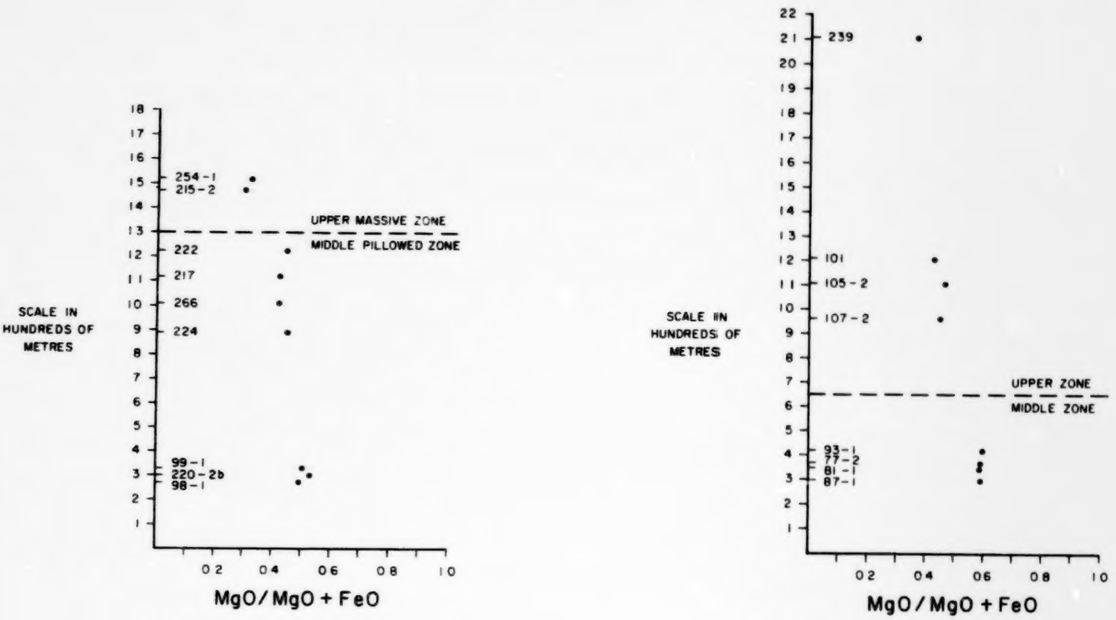
b. TiO_2 vs MgO



c. NiO vs MgO/MgO + FeO

d. Cr_2O_3 vs MgO/MgO + FeO

FIGURE 26: Chemical variation of Fox River volcanic rocks — binary variation diagrams



a. CHANGE IN MgO/MgO + FeO WITH STRATIGRAPHIC HEIGHT, LOWER VOLCANIC FORMATION

b. CHANGE IN MgO/MgO + FeO WITH STRATIGRAPHIC HEIGHT, UPPER VOLCANIC FORMATION

c. CHANGE IN TiO_2 WITH STRATIGRAPHIC HEIGHT, LOWER VOLCANIC FORMATION

d. CHANGE IN TiO_2 WITH STRATIGRAPHIC HEIGHT, UPPER VOLCANIC FORMATION

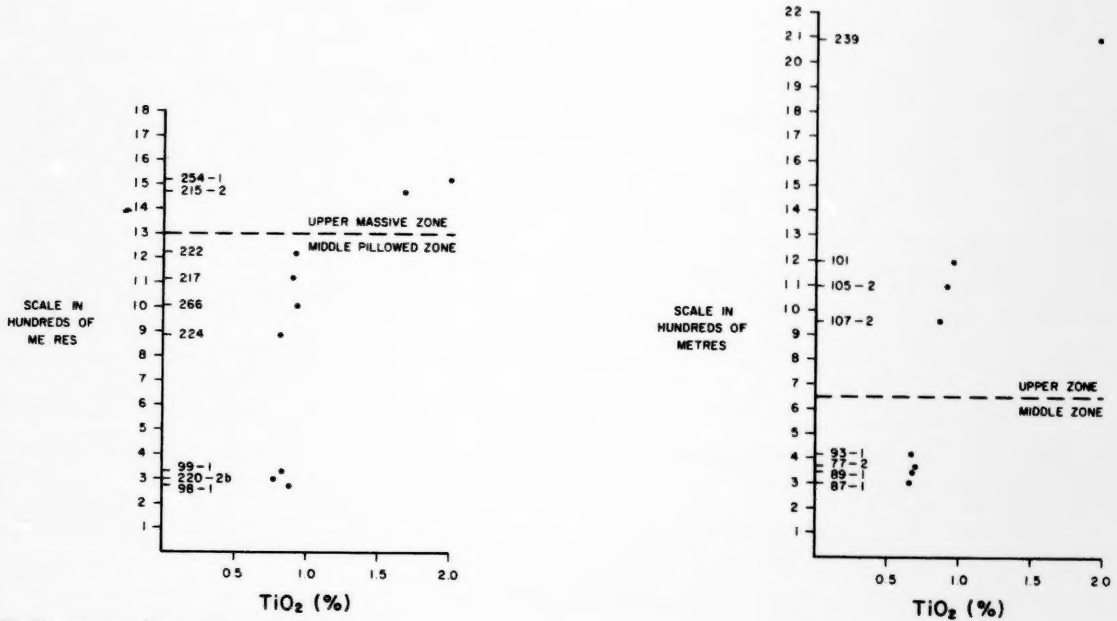


FIGURE 27: Chemical variation with stratigraphic height

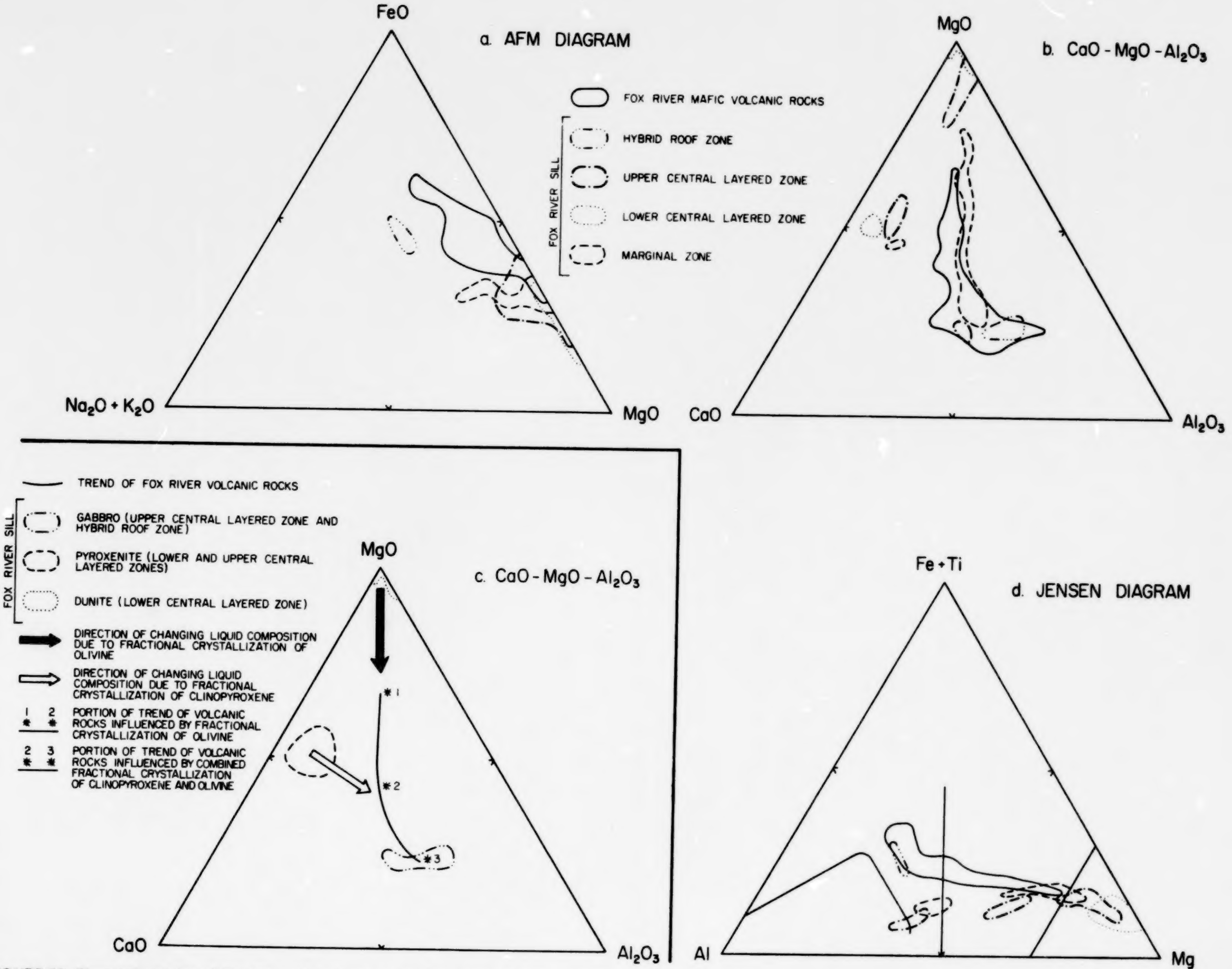


FIGURE 28: Chemical variation of Fox River volcanic rocks and Fox River Sill rocks — ternary variation diagrams.

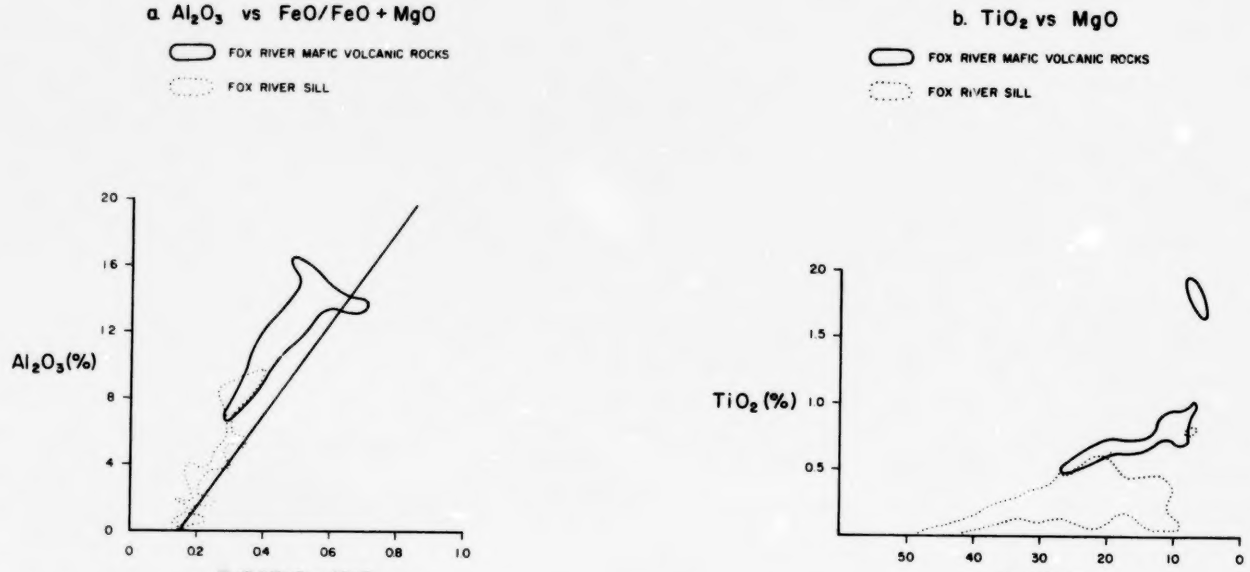


FIGURE 29: Chemical variation of Fox River volcanic rocks and Fox River Sill rocks — binary variation diagrams.

sive liquids reached the surface and formed lava flows. Thus, the liquid trend can be considered the trend for lavas which extends away from the MgO corner (Fig. 28c), and becomes curvilinear and convex toward the CaO-MgO join. The straight part of the trend above the inflection point reflects the affect of olivine fractionation, whereas the curvilinear part below the inflection point reflects the influence of pyroxene fractionation. The liquid trend terminated in the field for Sill gabbros. Thus, in an unrefined way, the trend of the fractionated crystals, and the evolved liquids can be compared directly on the CaO-MgO-Al_2O_3 diagram. The gabbroic rocks of the Sill depart from the trend of the lavas in the Jensen cation diagram (Fig. 28d); however, the trend of the lavas is extended back into the komatiite field by the olivine-, and pyroxene-rich cumulus rocks of the Sill. The lavas and Sill rocks form slightly overlapping, contiguous fields in the Al_2O_3 vs FeO/FeO + MgO, and TiO_2 vs MgO diagrams (Figs. 29a and 29b). The overlapping and contiguous nature of the Sill, and lava fields in the chemical variation diagrams strongly suggests that the Sill and lavas are part of a consanguineous suite. The conclusion derived from petrologic data that the lavas represent a succession of liquids derived from a chamber in which fractional crystallization took place is thus reinforced by the chemical data.

KOMATIITES AND THOLEIITES

The fact that tholeiitic rocks, which occur at the top of each volcanic formation, appear to represent the end point of each lava suite is an interesting aspect of the data. The indication is that lavas of komatiitic character can be consanguineous with tholeiitic lavas. Given that the origin of the flows is ascribed to a series of liquids, that are derived from liquids undergoing fractional crystallization in a subvolcanic chamber, the conclusion would seem to be that tholeiitic liquids can be generated by fractional crystallization of komatiitic liquid. This is significant, in that Francis and Hynes (1979) have documented the production of tholeiitic liquids from komatiitic initial magmas in Proterozoic mafic/ultramafic rock sequences of the Cape Smith-Wakeham Bay Belt of northern Quebec. They have suggested that komatiitic parent magmas produce tholeiitic daughters via fractional crystallization within shallow sills. Thus, it appears that the same, or a very similar mechanism is involved in the "transition" from komatiite to tholeiite in Cape Smith and Fox River volcanic sequences.

KOMATIITES OF THE CHURCHILL-SUPERIOR BOUNDARY ZONE

Scoates and Macek (1978) have noted that suites of mafic rocks, displaying komatiitic chemical characteristics, include the Molson dyke swarm, and some mafic volcanic rocks of the Ospwagan group of the Thompson Nickel Belt. Thus, the northwestern part of the Superior Province, including the Churchill-Superior boundary zone, is characterized in part, by mafic and ultramafic rock suites, displaying komatiitic chemical characteristics. This is illustrated in Figures 30 and 31, where the five major chemical variation diagrams have the fields for the Fox River mafic volcanic suite compared with the fields for the Molson dyke swarm (Scoates and Macek, 1978), and Ospwagan group mafic volcanic rocks of the Thompson Nickel Belt (data from Stephenson, 1974). In each case, the various fields are overlapping, indicating that each of these suites has nearly identical chemical characteristics. The serial or coherent nature of the trends for each of these suites is also clearly visible.

As previously noted, the Fox River rocks are of Aphebian age, although whether they are early or late Aphebian is unknown. The best age estimate for the Molson dyke swarm is approximately middle Aphebian (1800 — 2000 Ga, Ermanovics and Fahrig, 1975). Scoates (unpublished abstract) has recently suggested that Ospwagan group rocks of the Thompson Nickel Belt are of Aphebian age. Thus, the northwest part of the Superior Province craton, and the Churchill-Superior boundary zone in Manitoba, are characterized by mafic/ultramafic rock suites of komatiitic character, and broadly Aphebian age.

The edge of the Superior Province craton is characterized by Proterozoic sequences of broadly similar age, stratigraphy and lithologies. The segments of Proterozoic rocks have been termed the Circum-Superior Belt (Baragar and Scoates, 1980). Thick sequences of mafic volcanic rocks are a common component of Circum-Superior Belt rocks, and komatiitic flows are known from the Cape Smith Belt (Schwarz and Fujiwara, 1977; Francis and Hynes, 1979), and the Ottawa Islands (Baragar and Lamontagne, 1980). Thus, a considerable part of the northern Circum-Superior Belt contains mafic volcanic rocks of komatiitic character.

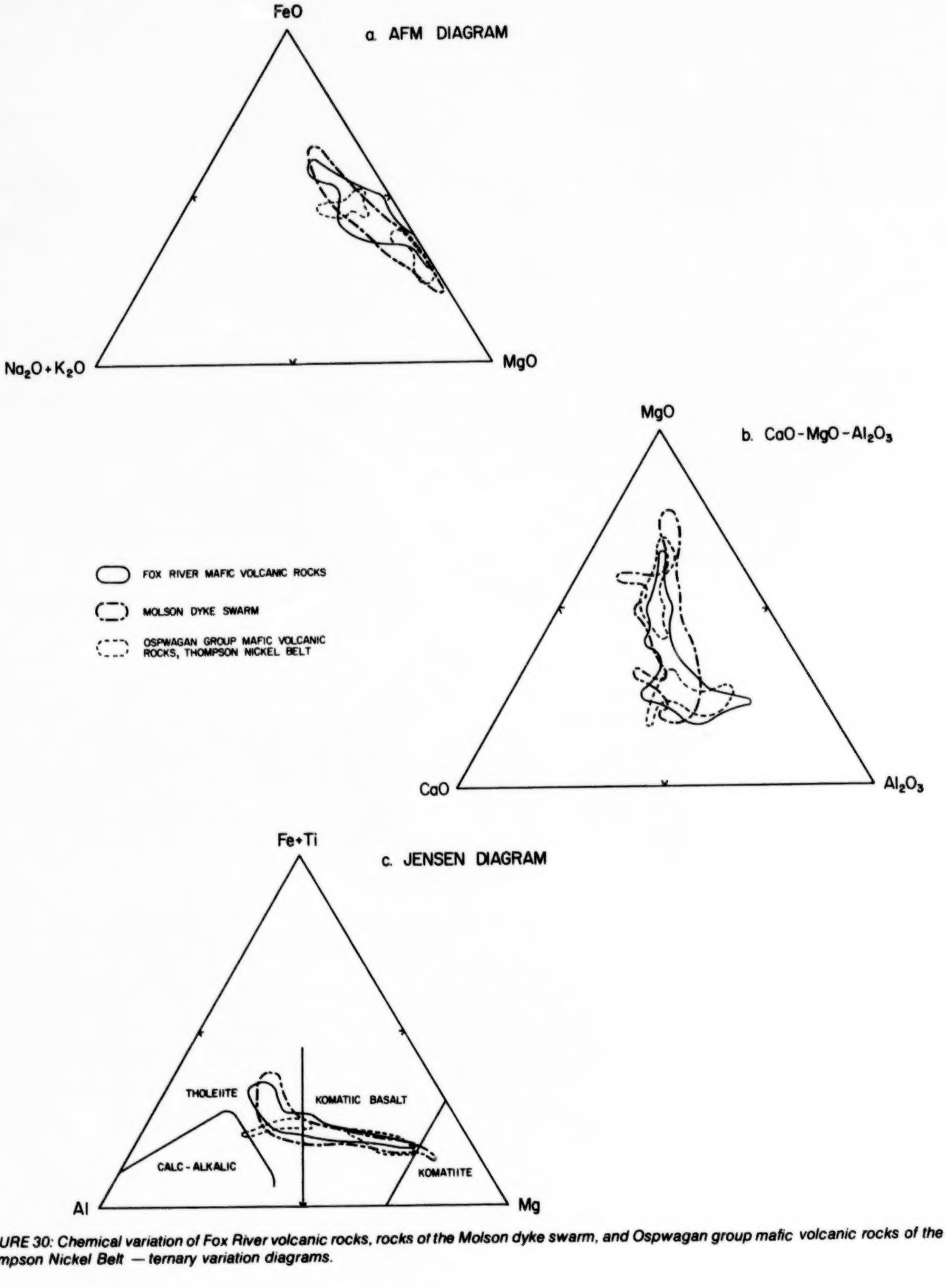


FIGURE 30: Chemical variation of Fox River volcanic rocks, rocks of the Molson dyke swarm, and Ospwagan group mafic volcanic rocks of the Thompson Nickel Belt — ternary variation diagrams.

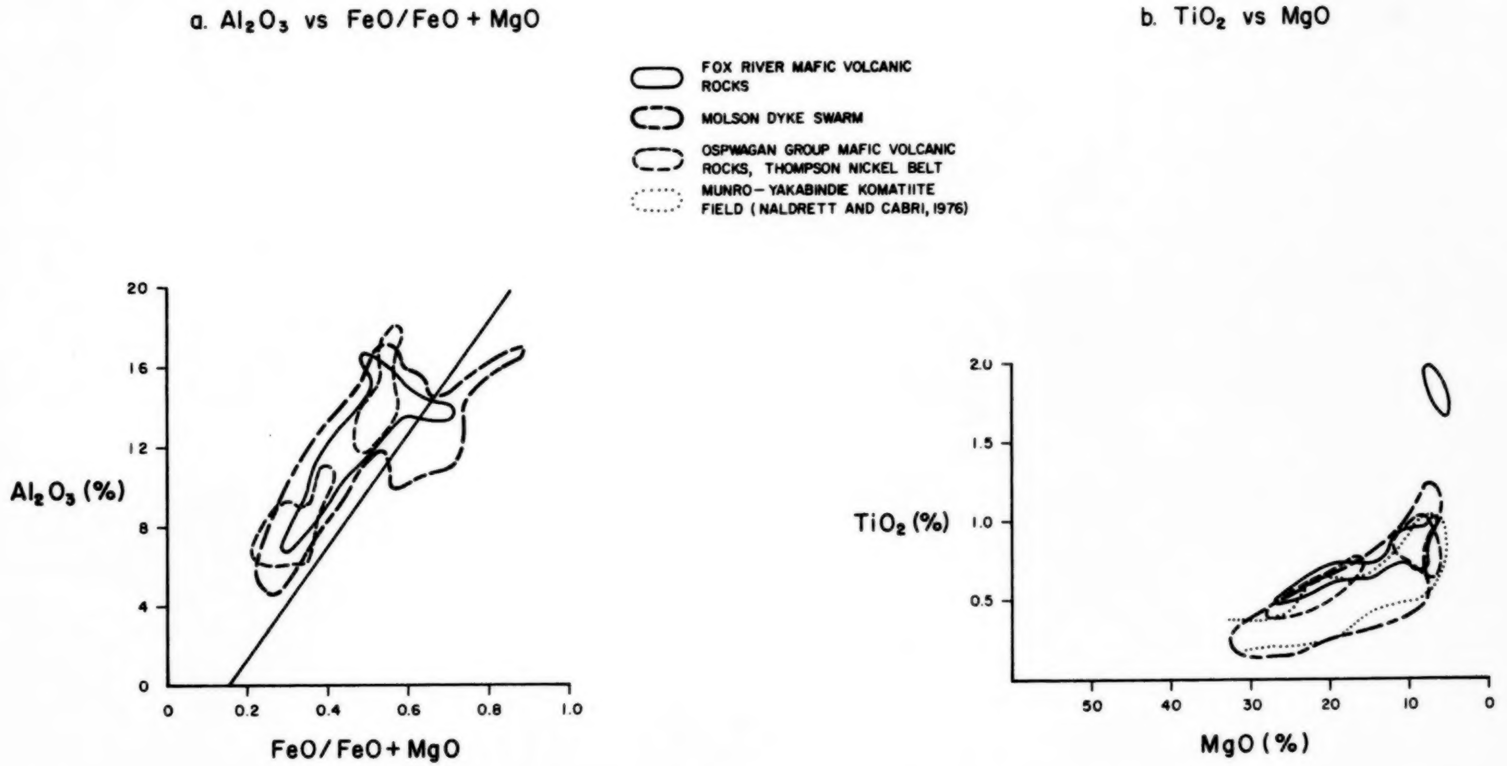


FIGURE 31: Chemical variation of Fox River volcanic rocks, rocks of the Molson dyke swarm, and Ospwagan group mafic volcanic rocks of the Thompson Nickel Belt — binary variation diagrams.

ORIGIN OF THE VOLCANIC ROCKS

CONSTRAINTS

The following discussion, conclusions, and models are based on investigations of available outcrops and diamond drill core. The scarcity of outcrops and their distribution, and the distribution of drill holes limits certain fundamental aspects of the study, the most important of which involve structural considerations. The general absence of folding is indicated by the consistent north-facing structures. The absence of major faults, parallel with the layering of units of the belt, cannot be unequivocally demonstrated. The general similarity of the volcanic formations, and the similar position of the underlying differentiated sills, suggests the possibility of repetition of units through faulting. However, on the basis of significant differences between the intrusive sills, and differences between the volcanic and sedimentary formations, large-scale repetition is considered to be unlikely. Faults with large offsets, that strike obliquely at high angles to the layering of the belt, are not obvious. However, serpentinite-picrolite breccias in Fox River Sill dunites and peridotites, and the difficulty in correlating in some areas, where drill holes are closely spaced, indicates that faults with some small-scale offsets may occur. The deformation observed in the stratigraphically lowest rocks observed in the belt is interpreted as indicating that the contact between these rocks and the gneissic rocks of the Superior Province craton is faulted. Given the constraints noted above, the continuity of the geology of the intrusive rocks, and the volcanic formations indicates that structural complexities within these units are not apparently significant.

SUBDIVISION OF THE VOLCANIC ROCKS

The two volcanic formations consist of rift- or fissure-like flows and each exceeds 2 km in thickness. The lavas of the volcanic formations have been subdivided on the basis of their morphological character into massive and pillowed zones. The rocks within each formation display a progressive change in mineralogical and chemical composition from base to top. Neither formation displays any signs of an hiatus, and the lavas are believed to represent a consanguineous suite of successive eruptions. A progression, from base to top from layered flows with olivine-rich cumulus rocks at their base, through pillowed, layered and massive flows that are olivine- and pyroxene-phyric, through to massive and pillowed flows that are plagioclase-phyric toward the top, has been recognized in both formations. The rocks were deposited subaqueously, and there is some indication that the lavas in the lower parts of each formation were deposited in the deepest water.

TEXTURES

Many of the rocks of the formations are characterized by unusual crystal morphologies and textures that are interpreted as implying their komatiitic character. The unusual textures are present in layered, massive, and pillowed flows, and in rocks of ultramafic and mafic composition. Olivine occurs as skeletal, hopper-shaped, sharply terminated crystals, ornamental chain-like crystals, and plate-like crystals. The plate-like olivine is uncommon, but where it occurs, it forms groups of parallel blades that define a microscopic spinifex texture. These types of crystals are most common in the upper parts of some layered flows, and in pillowed olivine clinopyroxenites.

Clinopyroxene occurs as delicate, frond-like, plumose crystals that are commonly curving or spiral-like, and that form fine-spun, interwoven masses. It also occurs as randomly disposed, individual, skeletal segments that possess characteristic bat wing- or M-shapes. In some cases, these skeletal individuals became oriented to produce straight, curving or spiral, chain-like crystals. Clinopyroxene also occurs as straight to slightly curving, blade-like crystals, some of which have a medial line and/or hollow space along their length. Clinopyroxene spinifex-textured rocks are composed of radiating bundles of these blade-like crystals. The cumulus clinopyroxenes of the clinopyroxenite zones of layered flows possess well-developed, hour-glass and sector zones. In mafic rocks, clinopyroxene forms dendritic to spherulitic crystals that commonly display a complex intergrowth with plagioclase. The clinopyroxene of the basalts of the upper parts of the two formations becomes increasingly anhedral and more strongly coloured.

Plagioclase occurs as dendritic to spherulitic crystals, many of which had hollow cores. Such plagioclase is common in the gabbros of layered flows. The originally hollow cores and spaces of the dendritic/spherulitic crystals are occupied by clinopyroxene. In the upper parts of some layered flows, plagioclase occurs as bundles of radiating, fibre-like crystals. It also occurs as skeletal, swallow-tail and belt buckle-shaped crystals in pillowed basaltic flows in the upper parts of the formation. Euhedral, lath-like plagioclase becomes more abundant toward the top of each formation, where a few examples of porphyritic basalts with plagioclase phenocrysts have been observed.

The primary textures noted above represent various amounts of departure from equilibrium crystallization. In experimental studies, there is a systematic variation in plagioclase crystal morphology, from tabular crystals to skeletal crystals, dendrites, and spherulites with increasing supercooling (Lofgren, 1974). Donaldson (1976) has shown, in experimental crystallization studies, that there is a systematic change from granular olivine to hopper, branching, randomly oriented chain, parallel-growth chain, chain + lattice, and plate or feather olivine with increase in cooling rate, and with increase in degree of supercooling. Lofgren *et al.* (1974) described pyroxene shapes as a function of cooling rate in the range from 1 to 2000° C / hr., such that with increasing cooling rate, pyroxenes became elongate and increasingly skeletal, at higher cooling rates the pyroxenes became dendritic and spherulitic, and at the most rapid cooling rates ($>$ 50° C/hr.) the pyroxenes were finely ornamented, feathery or fan-spherulitic arrays of acicular fibres, often complexly interwoven. Arndt and Nesbitt (1980) proposed that discrepancies in experimental studies on magnesian basalt associated with Archean komatiites, as well as the unusual compositions and habits of the pyroxenes, suggested that they grew metastably under conditions of high supercooling.

The widespread distribution of unusual crystal morphologies of olivine, pyroxene and plagioclase in Lower and Upper volcanic formation rocks, implies that these lavas crystallized under conditions that led to high degrees of supercooling and/or rapid cooling. The progressive decrease in abundance of these unusual crystal morphologies and textures with stratigraphic height indicates that metastable crystallization was gradually replaced by more normal, or equilibrium crystallization toward the top of each volcanic formation. The obvious change in composition of the rocks with stratigraphic height suggests that lava composition may have played a significant role in establishing the conditions under which nucleation and crystallization took place. For example, the progressive change from ultramafic (olivine clinopyroxenite) to mafic (basalt) flows indicates that extrusion temperatures of the lavas would decrease. In reference to olivine, Donaldson (1976) suggested that high normative olivine content of a magma, and very high eruption temperatures produce rapid growth leading to skeletal and spinifex-textured varieties. Thus, lava composition and eruption temperature can be significant in the subsequent nucleation and crystallization history.

VOLCANISM AND MAGMATISM: A PROPOSED MODEL[1]

The progressive change, in mineralogical and chemical composition with stratigraphic height in each volcanic formation, indicates derivation of the lavas from source chambers in which differentiation was taking place. The differentiated intrusions, underlying each of the formations, are considered obvious choices for such chambers, and this proposal is reinforced by the continuity of various chemical parameters between the flows and the Fox River Sill. The lava flows are considered to represent a succession of liquids, derived from the chamber, at different times in its evolution. The liquids are therefore evolved. This is important, because it means that all of the lava flows, including the most magnesian, do not represent original or primary liquids. The nature of liquid evolution has been demonstrated on the $\mathrm{CaO\text{-}MgO\text{-}Al_2O_3}$ ternary diagram (Fig. 28c), where the control of olivine fractionation, and subsequently pyroxene fractionation on the trend of the lavas can be seen. The decreasing $\mathrm{MgO/MgO + FeO}$ ratio, and the increasing $\mathrm{TiO_2}$ content of the lavas with stratigraphic height, also illustrate the progressively evolved nature of the flows of each formation. The culmination of liquid evolution is manifest in the development of high-Ti tholeiites at the top of each volcanic sequence. The direct implication is that tholeiites can be derived from komatiitic liquid by strong fractional crystallization, a conclusion reached by Francis and Hynes (1979).

The relationship between the lava flows and the intrusive sills can explain the dominant pyroxenitic character of the flows, and the lack of olivine spinifex-textured rocks suggestive of peridotitic liquids. The original liquids may have been peridotitic in composition prior to their reaching the chamber; however, after efficient fractional crystallization, and the removal of substantial amounts of olivine, the ratio of normative olivine to normative pyroxene would be reduced to the point where the liquid was pyroxenitic in composition. The large volumes of dunite and peridotite in the Fox River Sill, and other differentiated intrusions attests to the efficient fractional crystallization of olivine, and thus if primary peridotitic liquid entered the chamber, it would leave relatively olivine deficient and pyroxene-rich. This model relates the flows of the Upper volcanic formation to the Fox River Sill in such a way that the variation in composition of the flows is related to changes in the Fox River Sill.

The Fox River Sill is composed of four lithostructural zones. From base to top these zones are, marginal zone, lower central layered zone, upper central layered zone, and hybrid roof zone (Fig. 32). Each zone is characterized by distinctive rock types, and all but the hybrid roof zone are distinguished by a regular arrangement of those units. Since there appears to be a consanguineous relationship between the Sill and the overlying lavas of the Upper volcanic formation, it is apparent that each of these zones will contribute to an understanding of the processes of fractional crystallization and volcanism.

The marginal zone consists of the repetitive cycle lherzolite (olivine cumulate), websterite (clinopyroxene cumulate), gabbronorite (plagioclase cumulate) (Fig. 33). The lherzolite and websterite are plagioclase-bearing, and although differentiation of liquid is evident, there has not been effective removal of crystals and liquid, with the result that some reaction between liquid and crystals has taken place. Each cycle appears to be complete, and consequently there may be only limited loss of liquid. It seems reasonable to conclude that little or no volcanic equivalents to the south marginal zone will be found. The lack of efficient crystal-liquid separation is illustrated on the $\mathrm{CaO\text{-}MgO\text{-}Al_2O_3}$ diagram (Fig. 28b), where the field for the marginal zone rocks is similar to, and overlaps the field of Fox River volcanic rocks, and is significantly different from fields for other Fox River Sill zones.

The lower central layered zone is composed of the repetitive cycle, dunite (olivine cumulate) - olivine clinopyroxenite (clinopyroxene cumulate) (Fig. 33). The zone averages 900 m in thickness in the western part of the Sill. Dunite is the dominant unit forming layers up to 200 m or more thick, whereas olivine clinopyroxenite layers average 10 m thick. The top of each doublet is considered to represent the end of a cycle of fractionation, but not necessarily one magma pulse. There may be smaller, as yet unrecognized cycles in the thick dunite layers. Thus, the sequences of cyclic units may represent successive batches of magma that reached the chamber. If each doublet represents one (or more) influxes of magma and subsequent fractionation, the top of each doublet signifies the replacement of the fractionated, and hence evolved magma, by fresh batches of primary magma. The replaced magma was flushed out, and some may have reached the surface to form lava flows.

The doublet dunite-olivine clinopyroxenite is considered to represent what Jackson (1970) referred to as beheaded, or incomplete units. The cyclic repetition in the south marginal zone, and upper central layered zone comprises three units, an olivine cumulate, a pyroxene cumulate and a pyroxene-plagioclase cumulate. The implication is that the pyroxene-plagioclase cumulate in the lower central layered zone was prevented from developing. It is suggested that the reason for this was the influx of new magma into the chamber, and the removal of old magma, prior to plagioclase reaching the liquidus. The evolved magma that would have been removed, would have been depleted, in a normative sense, in olivine and consequently enriched, in a normative sense, in pyroxene and plagioclase. Successive liquids, removed at the end of fractionated cycles of the lower central layered zone type, would have been pyroxenitic in composition. As previously noted, it is possible that individual dunite layers may have been the result of more than one magma pulse, so that less evolved liquids could have reached the surface. The liquids might have had olivine on the liquidus, and might have contained olivine (± chromite) crystals in suspension. Liquids derived at different times in the development of the lower central layered zone could have had olivine or pyroxene on the liquidus, might have contained olivine ± pyroxene ± chromite crystals in suspension, would have been olivine-depleted to some extent, compared with the primary liquid that originally occupied the chamber, and consequently would have been relatively enriched in normative pyroxene and plagioclase. Olivine-bearing, and pyroxenitic lavas of the lower and middle zones of the volcanic formations could have originated from such liquids.

Layered flows, with lower olivine-rich zones composed of cumulus polyhedral ± skeletal olivine crystals, may represent liquids flushed out of the chamber with olivine on the liquidus, so that the lava at eruption consisted of liquid and suspended crystals. The liquid composition was pyroxenitic and this is supported by the olivine-deficient, pyroxene-rich marginal zones encountered in

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[1] *Since there is considerably more data for the Fox River Sill than for the Lower Differentiated intrusion, the magmatism-volcanism concept relates to the Sill and Upper Volcanic formation, although the progressive changes in mineralogical and chemical character of Lower Volcanic formation rocks suggest that the concept may well apply to the relation between those rocks and the Lower Differentiated intrusions.*

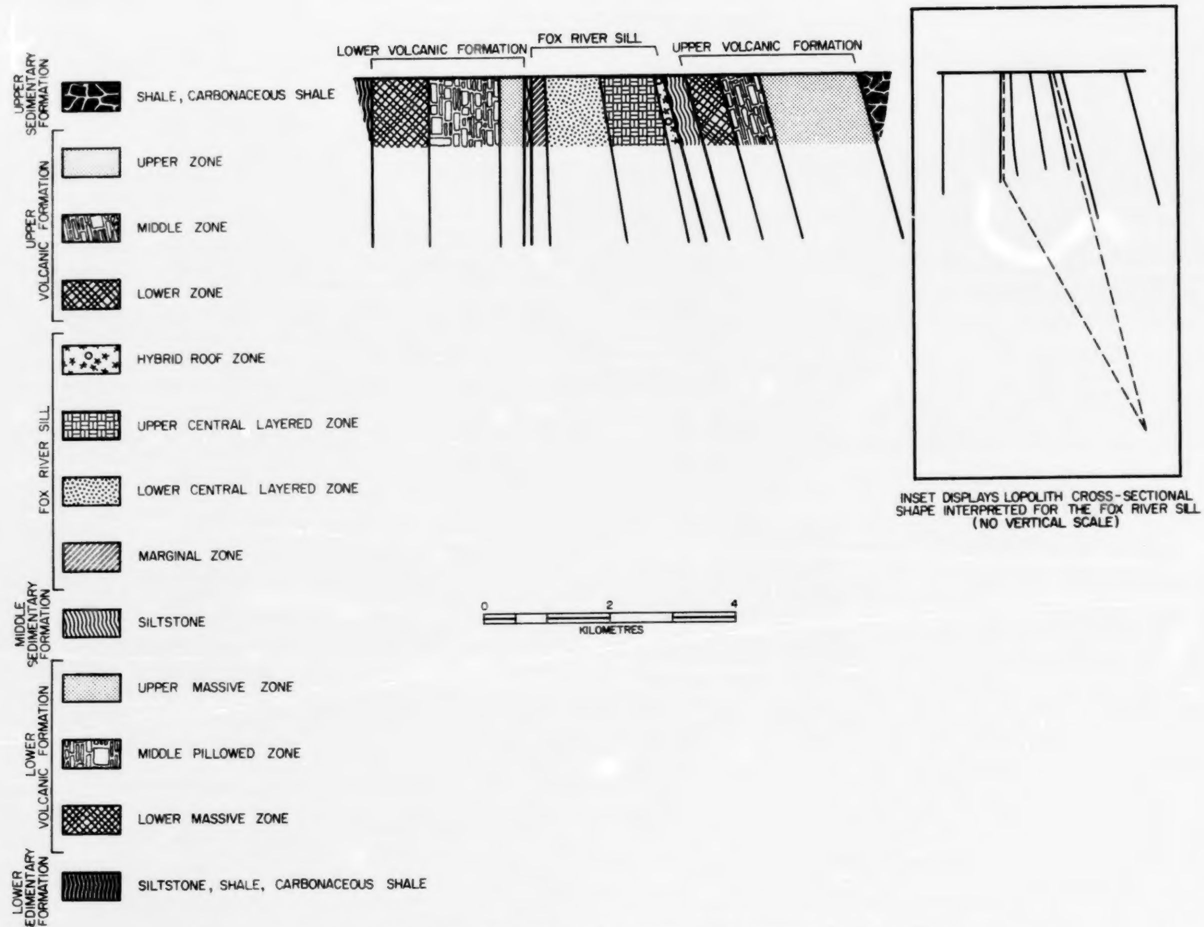

LOWER VOLCANIC FORMATION
FOX RIVER SILL
UPPER VOLCANIC FORMATION
UPPER SEDIMENTARY FORMATION
SHALE, CARBONACEOUS SHALE
UPPER VOLCANIC FORMATION
UPPER ZONE
MIDDLE ZONE
LOWER ZONE
FOX RIVER SILL
HYBRID ROOF ZONE
UPPER CENTRAL LAYERED ZONE
LOWER CENTRAL LAYERED ZONE
MARGINAL ZONE
MIDDLE SEDIMENTARY FORMATION
SILTSTONE
LOWER VOLCANIC FORMATION
UPPER MASSIVE ZONE
MIDDLE PILLOWED ZONE
LOWER MASSIVE ZONE
LOWER SEDIMENTARY FORMATION
SILTSTONE, SHALE, CARBONACEOUS SHALE
0
2
4
KILOMETRES
INSET DISPLAYS LOPOLITH CROSS-SECTIONAL SHAPE INTERPRETED FOR THE FOX RIVER SILL (NO VERTICAL SCALE)

FIGURE 32: Section, looking west, illustrating relationship of Fox River Sill to rocks of the Upper volcanic formation

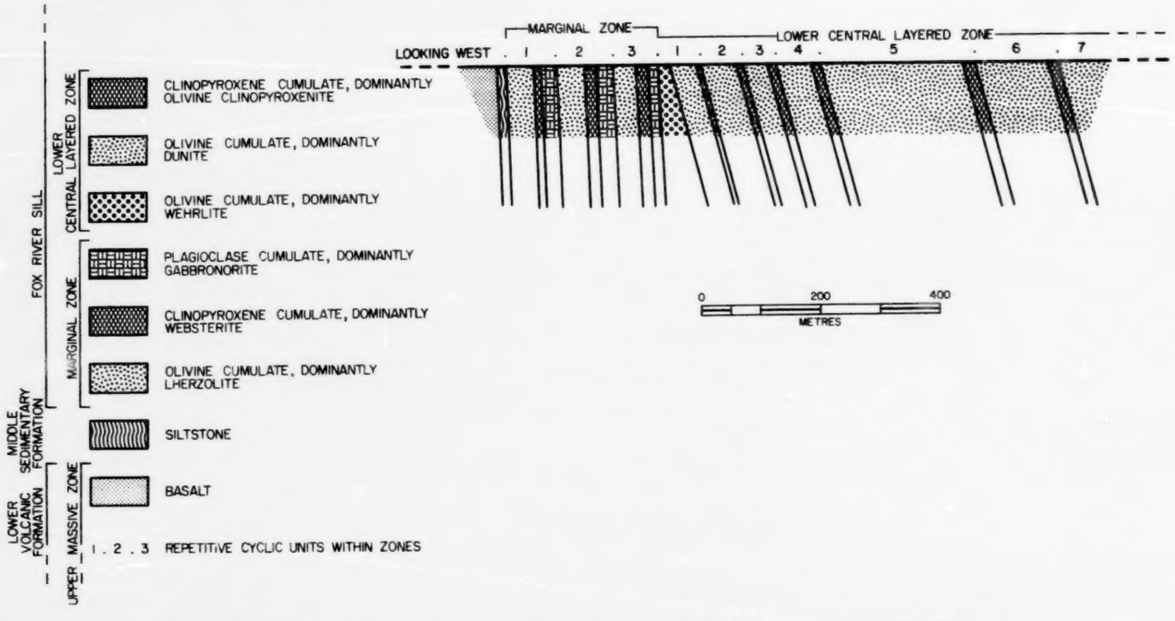

MARGINAL ZONE
LOWER CENTRAL LAYERED ZONE
LOOKING WEST . 1 . 2 . 3 . 1 . 2 . 3 . 4 . 5 . 6 . 7
FOX RIVER SILL
LOWER CENTRAL LAYERED ZONE
CLINOPYROXENE CUMULATE, DOMINANTLY OLIVINE CLINOPYROXENITE
OLIVINE CUMULATE, DOMINANTLY DUNITE
OLIVINE CUMULATE, DOMINANTLY WEHRLITE
MARGINAL ZONE
PLAGIOCLASE CUMULATE, DOMINANTLY GABBRONORITE
CLINOPYROXENE CUMULATE, DOMINANTLY WEBSTERITE
OLIVINE CUMULATE, DOMINANTLY LHERZOLITE
MIDDLE SEDIMENTARY FORMATION
SILTSTONE
LOWER VOLCANIC FORMATION
UPPER MASSIVE ZONE
BASALT
1 . 2 . 3 REPETITIVE CYCLIC UNITS WITHIN ZONES
0
200
400
METRES

FIGURE 33: Marginal zone and part of the lower central layered zone, Fox River Sill, Great Falls outcrop area, Fox River

most of the layered flows. The presence of skeletal, hopper, and ornamental chain olivine crystals in fine grained flow tops of layered flows, and in some pillowed flows indicates that some olivine was capable of crystallizing from the liquid after eruption.

The upper central layered zone is characterized by the repetitive cycle lherzolite, websterite, gabbronorite. The end of each cycle signifies the termination of a cycle of fractionation caused by the influx of new magma. The magma thus removed would have been more highly evolved than that removed at various times from the lower central layered zone. Fractionation cycles of shorter duration could have flushed out less-evolved magma. The liquid removed at the end of the obvious fractionation cycles would be olivine-depleted, and pyroxene and plagioclase would be on the liquidus. It is possible that pyroxene + plagioclase crystals might have been carried in suspension during replacement and eruption of the liquid. Lavas of this description occur in the upper zones of the volcanic formations and could have originated in this fashion.

The hybrid roof zone, the uppermost zone of the Fox River Sill, and the uppermost zone of many lower differentiated intrusions, is a chaotic mixture of medium to coarse grained gabbro with pegmatitic zones, quartz-bearing gabbro, and abundant granophyre-bearing rocks, and quartz-rich sedimentary rocks in various stages of reconstitution. Large, trellis-like, skeletal crystals of sphene, pseudomorphously replacing ilmenite, typify this zone. The Ti-rich lavas of the uppermost part of the volcanic formations may have originated from liquids flushed out from this uppermost zone of the intrusion.

As previously noted, others have concluded that the repetition of cyclic units in layered intrusions is caused by the introduction of successive batches of fresh magma into the chamber of differentation (see discussion in Jackson, 1970). Irvine and Smith (1967), in a discussion of the Muskox Intrusion, proposed that the magma that was replaced probably reached the surface as volcanic fissure eruptions. They also stated that other ultramafic bodies may have formed in subvolcanic reservoirs, and that many volcanic series show chemical variations attributed to fractional crystallization. In the Fox River Belt there is strong evidence for the kind of relationship between intrusions and lava flows proposed by Irvine and Smith.

The proposed relationship between major subdivisions of the Fox River Sill and possible extrusive equivalents of the Upper Volcanic formation, along with the similarity in their liquidus phases is illustrated in Table 3. A sequence of sketches illustrating some aspects of the proposed model relating the Fox River Sill to Upper Volcanic Formation lavas is shown in Figures 34 and 35.

The petrographic and geochemical evidence suggests a consanguineous relationship between the intrusions and the overlying volcanic formations. A model of this relationship has been presented, and is used to explain the apparent lack of olivine spinifex-textured rocks in the lava flows. The identification of olivine spinifex-textured rocks is important for demonstrating the presence of peridotitic liquids, which are, in turn, fundamental in their relationship to some types of Ni-sulphide deposits. The enormous volume of olivine-rich cumulates (dunite, peridotite), compared with the relatively small volume of pyroxenite and gabbro in the sill, and the dominant komatiitic basalt nature of the flows, suggests derivation of these rocks from a primary liquid of peridotitic composition. The proposed model suggests that peridotitic liquid, capable of crystallizing substantial volumes of dunite, reached high level magma chambers where it underwent fractional crystallization. The liquids that reached the surface to form flows had their normative olivine content reduced sufficiently, through fractional crystallization of olivine, that they were unable to develop olivine spinifex-textured rocks upon crystallization. Abundant pyroxene spinifex-textured rocks, and unusual crystal morphologies of olivine, pyroxene and plagioclase indicate that the conditions required for the development of such textures existed at the time of eruption of the flows.

Olivine spinifex-textured rocks have thus far not been observed in the komatiitic lavas of the Cape Smith Belt (Francis and Hynes, 1979); however, peridotitic komatiites with olivine spinifex have recently been described from the Ottawa Islands, in northeastern Hudson Bay (Baragar and Lamontagne, 1980). A lack of olivine spinifex-textured rocks in Aphebian komatiitic lavas of the Circum-Superior Belt suggests that this feature may be characteristic of these rocks.

TECTONIC IMPLICATIONS AND TECTONIC MODELS

Rocks of the Fox River Belt are interpreted to have been deposited upon Archean rocks of the Superior Province craton. This interpretation is based on the inference that Fox River rocks are analogues to similar rocks in other parts of the Circum-Superior Belt (Baragar and Scoates, op. cit.). The nearest example of an unconformable relationship is found in the Sutton Inlier, some 400 km east of the Fox River Belt (Bostock, 1971). Other examples have been described from Lac Guillaume Delisle (Richmond Gulf), the Cape Smith Belt, and the Labrador Trough. In the northern part of the Labrador Trough, Archean basement is found on both sides of the Trough indicating that it may be an intracratonic basin developed at or near the edge of contiguous Archean, Superior Province crust. The relationship of the supracrustal rocks of the Circum-Superior Belt to the Archean basement is similar among various segments of the Belt, in that basement underlies most or all of the recognizable rocks, including the volcanic successions (Baragar and Scoates, op. cit.). Thus, it is not unreasonable to suggest that Fox River Belt rocks might also have been deposited in an intracratonic basin developed at or near the edge of the Archean, Superior Province craton.

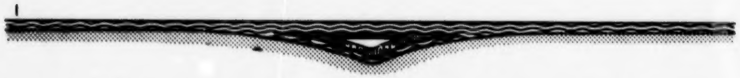
As previously noted, the northwest part of the Superior Province craton and the Churchill-Superior boundary zone are characterized by intrusive and extrusive rocks of komatiitic nature. The Molson dykes indicate crustal extension of several kilometres, possibly as much as 10 km (Scoates and Macek, op. cit.). The abundance of ultramafic and mafic rocks and rift-type volcanic rocks in the Fox River and Thompson Nickel Belts implies crustal attenuation and indicates that tensional forces existed that were capable of splitting the crust underlying the basins (Fig. 36). There is strong evidence, therefore, of a close relationship between tensional stress, and komatiitic magmatism (Molson dykes, Fox River Sill and differentiated intrusions: Ospwagan group ultramafic rocks of the Thompson Nickel Belt) and volcanism (Fox River and Ospwagan group volcanic rocks) in the northwest part of the Superior Province, and along the edge of the Superior Province craton, during Aphebian time.

If Fox River Belt rocks originated by deposition in an intracratonic basin, they would represent one of many examples of intracratonic, Proterozoic basins containing volcanic sequences that imply rifting of continental crust. Other examples, known from widely separated regions of the Canadian Shield, include the Lake Superior structure and Lake Huron structure (Sims *et al.*, 1980; Innes and Bennett, 1980), the Borden Basin, Baffin Island (Jackson and Iannelli, 1980), the Baker Lake Basin in the District of Keewatin (Le Cheminant and Eade, 1980). Some basins are believed to have formed in response to

FOX RIVER SILL						UPPER VOLCANIC FORMATION		
Subdivisions	Cumulus phases	Other distinctive minerals	Cyclic units	Possible liquidus minerals for liquids expelled before the end of a cycle	Possible liquidus minerals for liquids expelled at the end of a cycle	Possible extrusive equivalent	First liquidus phase	Morphological characteristics of primary minerals
Hybrid roof zone	plagioclase	ilmenite, quartz	none	plagioclase	plagioclase	high-TiO_2, Upper zone plagioclase-phyric basalt	plagioclase	lath-like plagioclase crystals
Upper central layered zone	olivine, clinopyroxene, plagioclase	chromite	peridotite, pyroxenite, gabbro	olivine, clinopyroxene	plagioclase	Upper-zone plagioclase-phyric basalt	plagioclase	lath-like plagioclase crystals, skeletal plagioclase crystals minor frond-like clinopyroxene
Lower central layered zone	olivine, clinopyroxene	chromite	dunite, olivine clinopyroxenite	olivine	clinopyroxene	Middle zone, olivine clinopyroxenite pillowed flows and olivine-and clinopyroxene-bearing layered flows. Lower zone olivine-and clinopyroxene-bearing layered flows	olivine, clinopyroxene	hopper, ornamental chain and polyhedral olivine crystals, M-and bat wing-shaped clinopyroxene crystals, frond-like and zoned prismatic clinopyroxene crystals
Marginal zone	olivine, clinopyroxene, plagioclase	chromite, ilmenite	peridotite, pyroxenite, gabbro	olivine, clinopyroxene	plagioclase	minor plagioclase-phyric basalt, Lower zone	plagioclase	lath-like plagioclase crystals

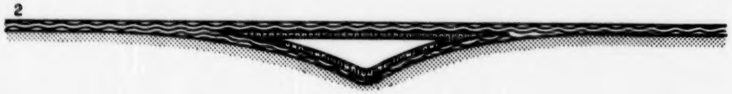
TABLE 3: Liquidus minerals, Fox River Sill lithostructural zones, and Upper Volcanic formation lava flows.

1



INTRODUCTION OF MAGMA INTO MIDDLE SEDIMENTARY FORMATION SILTSTONE AND BEGINNING OF CRYSTALLIZATION OF MARGINAL ZONES. FOX RIVER SILL CHAMBER BECAME LARGER WITH SUCCESSIVE MAGMATIC INJECTIONS.

2



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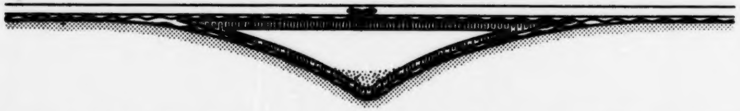
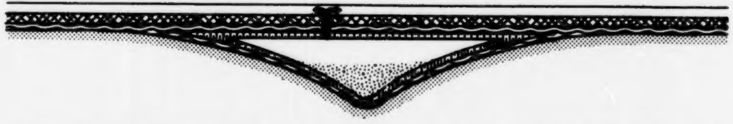


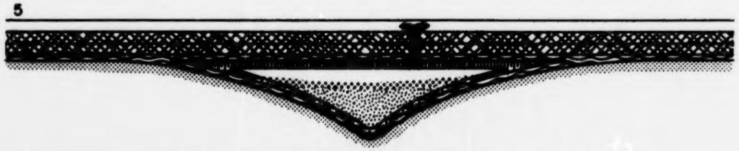
COMMENCEMENT OF FRACTIONAL CRYSTALLIZATION IN FOX RIVER SILL CHAMBER. MAGMATIC FLUID THAT WAS FLUSHED OUT AND REPLACED AND THAT REACHED THE SURFACE TO FORM LAVA FLOWS COULD HAVE HAD EITHER OLIVINE OR CLINOPYROXENE ON THE LIQUIDUS. THE OLIVINE-AND CLINOPYROXENE-BEARING LAYERED FLOWS OF THE LOWER ZONE CRYSTALLIZED FROM LIQUIDS OF THIS TYPE.

4



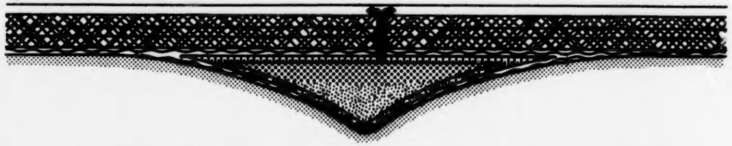
FRACTIONAL CRYSTALLIZATION CONTINUED AND THE PILE OF CUMULUS CRYSTALS GREW. OLIVINE ± CLINOPYROXENE ± CHROMITE WERE STILL THE DOMINANT PHASES. MAGMATIC FLUID FLUSHED OUT AT THE END OF THE REPETITIVE CYCLES (DUNITE-OLIVINE CLINOPYROXENITE) WOULD HAVE HAD CLINOPYROXENE ± OLIVINE ON THE LIQUIDUS. THE PILLOWED OLIVINE CLINOPYROXENITE FLOWS AND OLIVINE-AND CLINOPYROXENE-BEARING LAYERED FLOWS AT OTTER FALLS ON THE STUPART RIVER REPRESENT FLOWS CRYSTALLIZED FROM SUCH LIQUIDS.

5



AS FRACTIONAL CRYSTALLIZATION PROCEEDED THE REPETITIVE CYCLE DUNITE-OLIVINE CLINOPYROXENITE (LOWER CENTRAL LAYERED ZONE) GAVE WAY TO CYCLES INVOLVING PERIDOTITE, PYROXENITE AND GABBRO (UPPER CENTRAL LAYERED ZONE). MAGMATIC FLUIDS THAT WERE FLUSHED OUT AND REACHED THE SURFACE AT THE END OF A CYCLE COULD HAVE GIVEN RISE TO PILLOWED AND MASSIVE PLAGIOCLASE-PHYRIC BASALT, SIMILIAR TO THAT EXPOSED AT JACKFISH FALLS ON THE STUPART RIVER.

6



CRYSTALLIZATION TERMINATED WITH THE FINAL CONSOLIDATION OF ROCKS OF THE HYBRID ROOF ZONE. THE ROOF ZONE IS DISTINGUISHED BY QUARTZ-BEARING ROCKS AND AN ABUNDANCE OF ILMENITE. FLUID FLUSHED OUT AND REACHING THE SURFACE FROM THIS ZONE COULD HAVE GIVEN RISE TO HIGH TiO_2 BASALT OF THE KIND OBSERVED IN THE FOX RIVER NORTH 3 OUTCROP AREA.

UPPER VOLCANIC FORMATION	▩	KOMATIITIC BASALT, BASALT
FOX RIVER SILL	▦	UPPER CENTRAL LAYERED ZONE
	░	LOWER CENTRAL LAYERED ZONE
	▥	MARGINAL ZONE, HYBRID ROOF ZONE
MIDDLE SEDIMENTARY FORMATION	≋	SILTSTONE
LOWER VOLCANIC FORMATION	▒	BASALT

EACH CROSS SECTION IS CONSIDERED TO REPRESENT A DIFFERENT POSITION ALONG THE 70 KM OF STRIKE LENGTH OF THE WEST LOBE OF THE FOX RIVER SILL. THERE IS NO FEEDER ILLUSTRATED IN ANY OF THE SECTIONS INDICATING THAT FRESH BATCHES OF MAGMA ENTERED THE CHAMBER AT SOME POINT OTHER THAN THOSE ILLUSTRATED. VARIOUS FEEDERS MAY HAVE BEEN ACTIVE AT DIFFERENT PLACES AT DIFFERENT TIMES.

NOT TO SCALE

FIGURE 34: Sequence of sketches illustrating some aspects of the proposed model relating Fox River Sill magmatism to the development of the lava flows of the Upper volcanic formation

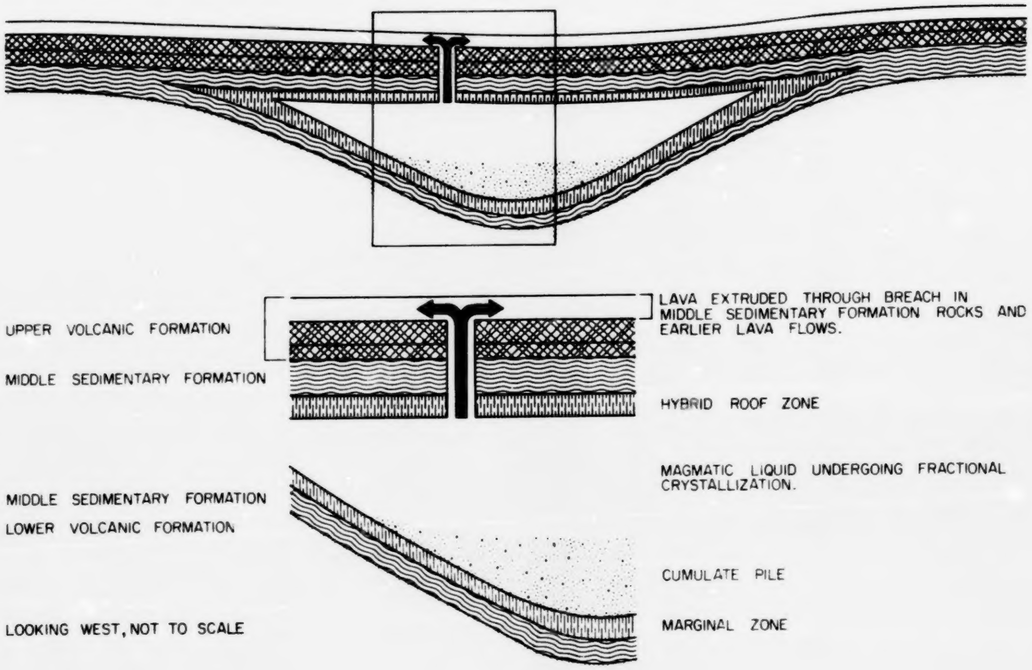
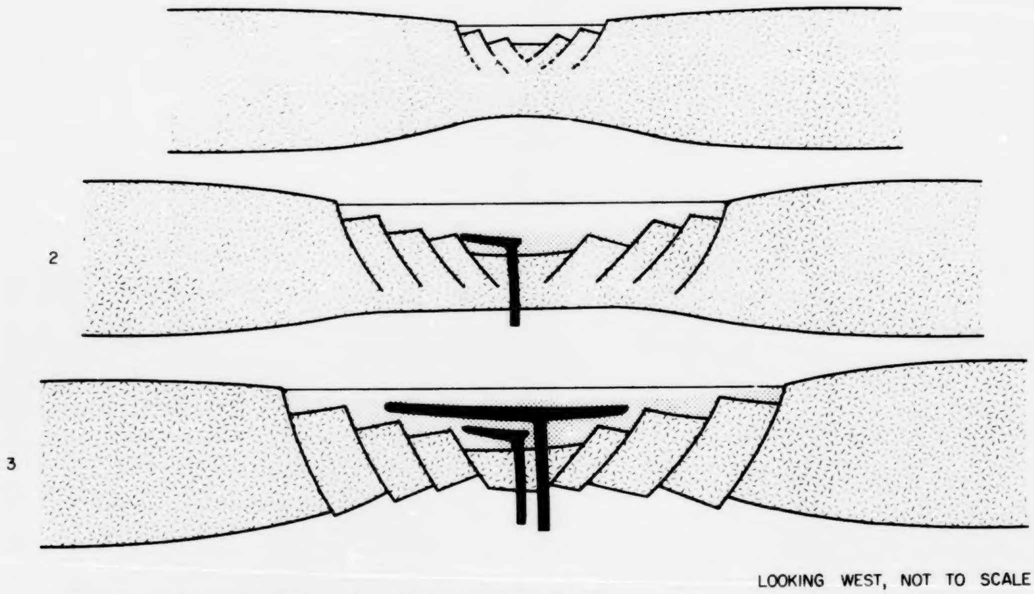

UPPER VOLCANIC FORMATION
MIDDLE SEDIMENTARY FORMATION
LAVA EXTRUDED THROUGH BREACH IN MIDDLE SEDIMENTARY FORMATION ROCKS AND EARLIER LAVA FLOWS.
HYBRID ROOF ZONE
MAGMATIC LIQUID UNDERGOING FRACTIONAL CRYSTALLIZATION.
MIDDLE SEDIMENTARY FORMATION
LOWER VOLCANIC FORMATION
CUMULATE PILE
LOOKING WEST, NOT TO SCALE
MARGINAL ZONE

FIGURE 35: Proposed, generalized relationship between magmatism and volcanism


2
3
LOOKING WEST, NOT TO SCALE

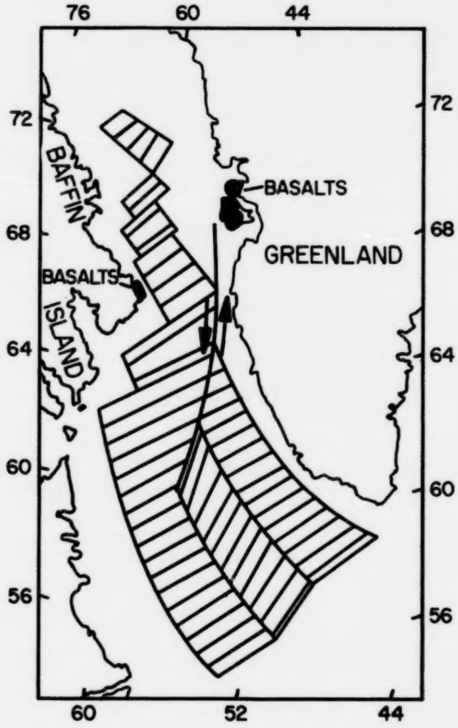
1) CRUSTAL ATTENUATION AND INITIAL DEVELOPMENT OF BASIN
2) AS TENSIONAL ENVIRONMENT CONTINUES, BASIN BECOMES LARGER AND BEGINS TO FILL WITH SEDIMENTARY AND VOLCANIC ROCKS (DOTS). SILL-LIKE INTRUSION IS SHOWN IN BLACK.
3) FINAL CONFIGURATION OF INTRACRATONIC BASIN.

FIGURE 36: Development of the Fox River basin

ocean-opening events in adjacent areas, and some are parallel to earlier structural trends in the underlying basement.

A relationship between Archean komatiitic rocks, tensional environments, and intracratonic basins has been suggested for the Belingwe greenstone belt, Rhodesia (Nisbet *et al.*, 1977) and the Yakabindie belt, Western Australia (Naldrett and Turner, 1977). The presence of sediments and granitic crust beneath the komatiitic lavas in the Belingwe belt implies that the lavas were not produced in an oceanic environment. Nisbett *et al.*, (op. cit.) also suggested that analogous modern rocks are produced in early crustal rifting or marginal basin environments, and that the Belingwe lavas were possibly produced in a similar tensional setting. Naldrett and Turner (op. cit.) used the proposed origin of the Baffin Bay Basin by rifting as an integral part of their model for the development of the Yakabindie Belt.

Rocks of the Fox River Belt may be analogous to rocks of the Triassic, Newark Basins that parallel the Atlantic coast from the Bay of Fundy to North Carolina. These intracratonic basins contain sedimentary rocks and interbedded basaltic flows and diabasic sills (Clark and Stearns, 1968). In addition, the Molson dyke swarm may be analogous to the diabase dykes of Triassic-Jurassic age that form swarms along the margin of the Atlantic Ocean in North America, South America and Africa. These dykes are considered to be the manifestation of the tensional stress field that existed in the crust immediately prior to the opening of the present Atlantic Ocean (May, 1971; Smith and Noltimier, 1979; Sutter and Smith, 1979). It is noteworthy that the tensional environment associated with the eastern margin of North America in Triassic time, which gave rise to the elongate intracratonic basins and the diabase dyke swarms, is significant in signalling the opening of the present Atlantic Ocean (Dalyrmple, *et al.*, 1975).



(AFTER LE PICHON ET AL., 1971)

FIGURE 37: Proposed two phases of opening of the Labrador Sea, showing Baffin Island and Greenland Tertiary basalts

Fox River Belt rocks have a possible Tertiary analogue in the Baffin Bay area of the Northwest Territories. Tertiary supracrustal rocks, exposed on Cape Dyer on Baffin Island, and on Disko Island and the Svartenhuk peninsula in West Greenland (Pulvertaft and Clarke, 1966; Clarke and Upton, 1970), unconformably overlie Aphebian gneiss (Fig. 37). The sedimentary rocks include non-marine and marine types, and the volcanic rocks include picrites and basalts. The volcanic rocks are primitive in that MgO values are high, and K_2O values are low (Clarke, 1970: Jamieson and Clarke, 1970). Clarke and Upton (op. cit.) concluded that the Baffin Island and West Greenland provinces were the fragments of one formerly continuous basalt plateau now separated by rifting, and intervening new oceanic crust (Fig. 37). They also proposed that the production of magma, and rifting of the continent are simply two phases of one major geological event and are, therefore, inseparable in either space or time. Keen *et al.* (1974) suggested that Baffin Bay is an ocean basin in the sense that it is underlain by crust with properties similar to those of oceanic crust in the main ocean basins.

The Triassic Newark basins and the Tertiary Baffin Bay basin developed through crustal extension and rifting, and in each case the tensional environment led ultimately to the production of oceanic crust. In the Baffin Bay example the spreading halted, and the amount of oceanic crust generated was small. The previously noted examples of Proterozoic basins also imply widespread tensional stress fields leading to attenuation and rifting of pre-existing crust. However, little or no evidence exists that rifting in Proterozoic time ultimately led to the generation of oceanic crust. Evidence from Archean greenstone belts in Rhodesia and Western Australia suggest that komatiitic belts were of an intracratonic nature and were produced in a tensional environment. In the case of the Yakabindie Belt, Naldrett and Turner (op. cit.) have suggested that rifting stopped before any oceanic crust was produced.

At Fox River, it is proposed that the formation of an intracratonic basin was followed by rifting of the underlying crust, and the intrusion and extrusion of substantial volumes of ultramafic and mafic rocks (Fig. 36). The lack of identified oceanic crust along the Churchill-Superior boundary zone suggests either, that the rifting was arrested prior to the development of oceanic crust, or that any oceanic crust that was produced was ultimately completely consumed. It is also possible that oceanic crust has not been identified because it was modified through subsequent metamorphic and tectonic events, or was originally significantly different from present oceanic crust. Recently, Lewry and Sibbald (1980) have proposed that changes in supracrustal assemblages, thermotectonism and character of Hudsonian plutonism from the Cree Lake Zone, east across the Rottenstone Complex into the Southeastern Complex in northern Saskatchewan, compares with the transition to island arc-oceanic crustal environments, and magmatic belts in younger orogens. Thus, there is a suggestion for a fundamental change in crustal character, and thus the possibility for the existence of oceanic crust in the Churchill Province.

Gibb and Walcott (1971) suggested that the Fox River Belt forms part of a proposed suture, that is marked by other segments of the northern part of the Circum-Superior Belt, a suggestion also proposed by Dewey and Burke (1973). A suture zone marks the boundary where two plates are welded together, and indicates a closing ocean basin. The collision of plates is a compressive event, and signifies a compressional environment of substantial proportions. Features indicative of plate collision such as melange zones, ophiolites, blueschist zones and zones of overthrusting are manifestly not evident in the Fox River Belt. Thus, if Precambrian suture zones are to be identified on the basis of features common to Phanerozoic suture zones, it is considered unlikely that the Fox River Belt forms part of Precambrian suture.

Some geological and geophysical features of the Churchill Province have been interpreted in terms of plate tectonic processes. Several suggestions for the placing of a suture in the middle of the Churchill Province orogen have recently been proposed (Camfield and Gough, 1977; Cavanaugh and Seyfert, 1977; and Ray and Wanless, 1980). Although none of the proposed sutures is situated exactly in the same place, they are all within the central part of the orogenic belt, rather than at or near its margin. A suture within the central part of the Churchill Province orogen fits much better with the proposed interpretation of the Fox River Belt.

The rocks of the Fox River basin have not escaped entirely from later deformation, and like most Circum-Superior basins a later compressional event has resulted in the final disposition of the rocks. The north-facing, steeply dipping, homoclinal nature of the Belt implies that the unexposed north contact between belt rocks and Churchill Province paragneiss is faulted. The exact nature of this contact is unclear; however, it may be that the paragneiss was thrust southward over rocks of the Archean craton and came in fault contact with Fox River Belt rocks (Fig. 38). The development of small-scale, and possible large-scale folds in sedimentary rocks of the Lower sedimentary formation (Scoates, in prep.), indicates that the contact between the sediments and the crystalline rocks of the Archean craton may be faulted. The final configuration of the rocks of the basin is interpreted to be due to thrusting of Churchill Province paragneiss over rocks of the Archean craton. The southward thrusting of paragneiss is not considered to represent an ocean-closing event, but rather seems to imply thrusting of cratonic crust over cratonic crust, the significance of which is presently unclear.

The significance of the Fox River Belt, and other Aphebian belts around the edge of the Superior Province craton, may be that they are precursors to the development of Aphebian oceanic crust. This oceanic crust may have been generated in the central parts of the Churchill Province orogen, and the closure of this oceanic terrain, and the subsequently developed suture may have been substantially "offshore" from the edge of contiguous Superior Province crust. Thus the features indicative of plate collision would be found within the Churchill Province, some distance from the Fox River Belt. By this model, the marginal basins would be older than about 1750 Ma. The proposed model relates these Aphebian basins to oceanic crust in a similar way that the Newark Basins are related to the present Atlantic ocean. This suggests, that if the other segment or segments of the rifted crust have not disappeared, or otherwise been completely reconstituted, the finding of Archean, Superior Province-like crust, with dykes similar in character to the Molson swarm, would have some merit in delineating the limits of the intervening mobile belt.

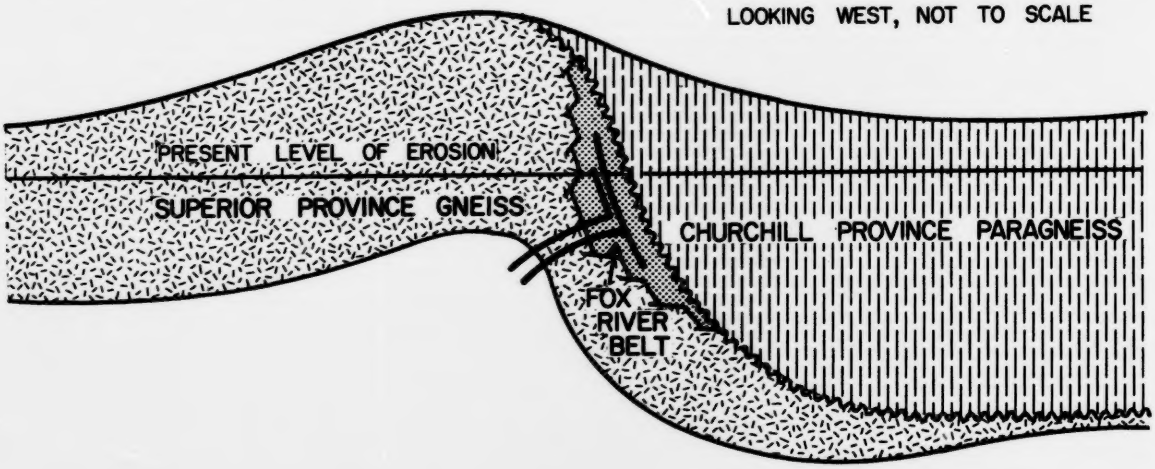


FIGURE 38: Sketch, looking west, illustrating a proposed, simple tectonic relationship between Churchill Province paragneiss, Fox River supracrustal rocks and crystalline rocks of the Archean craton. The disposition of rock masses seen in the Fox River area is the same as that intersected by the line representing the present level of erosion in the sketch. Although the actual tectonic relationship is undoubtedly more complex, the mechanism whereby Churchill Province rocks are thrust over rocks of the Archean craton and are in fault contact with Fox River rocks is considered reasonable.

ECONOMIC GEOLOGY

MINERALIZATION

Sulphide minerals are common though not abundant constituents of the volcanic rocks, and concentrations of sulphide minerals in the lavas have not been observed. Pyrrhotite is the dominant mineral, and occurs as highly irregular, ragged grains, dust-like patches, and partial vein fillings. It originally formed an interstitial accessory mineral in most rocks. Pyrite and chalcopyrite are much less common, and pentlandite was identified from the olivine-rich zone of one layered flow from the Upper volcanic formation.

The only concentrations of sulphide minerals in the volcanic formations are associated with the carbonaceous shales that separate successive flow units in some areas. The sulphide minerals occur dominantly as very fine grained, dull, earthy, lustreless mixtures with graphite, as veinlets cutting the lamination of the shales and as patch-like concentrations. Pyrrhotite is the dominant sulphide mineral identified in this association. Pyrite crystals and chalcopyrite stringers are associated with pyrrhotite in some rocks. In some examples, the concentration of finely disseminated sulphides enhances the delicate lamination of the carbonaceous shale.

POTENTIAL FOR NICKEL SULPHIDE DEPOSITS

The recognition of substantial volumes of dunite and peridotite, in high level, subvolcanic chambers associated with komatiitic volcanic suites in the Fox River Belt, is significant in pointing to a high potential for concentration of nickel sulphides. The apparent consanguineous relationship between lava flows, and differentiated intrusions has been explained by a model, relating the development of the intrusions to successive impulses of pyroxenitic to peridotitic magma. The absence of later magmatic events and the lack of later tectonic events implies that, if ore deposits developed, they would have developed as primary concentrations of nickel sulphide related to the intrusive and extrusive magmatic events. Nickel sulphide deposits are associated directly with komatiitic lava flows (Kambalda, Western Australia), and they are hosted by olivine-rich, dunite-peridotite lenses and/or sills in komatiitic sequences (Mt. Keith-Perseverence, Western Australia; Cape Smith subeconomic deposits, northern Quebec).

Ultramafic rocks, associated with Aphebian supracrustal rocks in portions of the Circum-Superior Belt, are hosts to significant concentrations of nickel sulphide mineralization. The nickel deposits of the Thompson Nickel Belt are associated with Ospwagan group ultramafic rocks, and with layered gneissic rocks of uncertain association. Although a relationship between nickel sulphide deposits, and ultramafic rocks is common in the belt, it is not ubiquitous, and the geological relationships within the belt have been complicated by events of deformation, metamorphism and plutonism. Subeconomic nickel sulphide deposits are associated with ultramafic rocks of the Cape Smith Belt of northern Quebec. Komatiitic rocks form important units in the Thompson Nickel Belt (Peredery, 1979), and in the Cape Smith Belt (Arndt, Francis and Hynes, 1979; Baragar and Scoates, 1980). The similarity in stratigraphy between the Fox River Belt and the Cape Smith Belt (Baragar and Scoates, op. cit.) implies that an examination of the nature of the nickel sulphide mineralization in the Cape Smith Belt would be fruitful in terms of whether similar concentrations might occur in Fox River Belt rocks.

The Katiniq, Cross Lake, and Donaldson deposits are estimated to contain slightly less than 20 million tons of ore, grading from 1.5 to 4.0% Ni and from 0.6 to 0.95% Cu (Dugas, 1971; Barnes, 1979). The Katiniq deposit is hosted by the Katiniq sill, a subhorizontal, shallow level, subvolcanic, ultramafic intrusion (Barnes, 1979). The nickel sulphide mineralization is restricted to the sill, where it forms basal accumulations, localized by irregularities in the footwall contact. Barnes proposed that the sill was emplaced by multiple injection of olivine xenocryst-bearing, pyroxenitic magma. He stated that the presence of significant amounts of accumulated olivine in a subvolcanic feeder system increased the effective viscosity of the magma sufficiently, so that it was capable of transporting sulphide liquid during magma ascent.

Miller (1977), in a study of another Cape Smith mineralized sill, concluded that the sill formed from the intrusion of olivine-rich magma as crystal mush. This intrusion was immediately followed by intrusion of an oxide-sulphide magma, and subsequent settling, and concentration of the sulphide melt in depressions along the base of the sill.

The ore deposits of the Cape Smith Belt are explained as being primary, and they originated because nickel sulphides were associated with intrusion of crystal-charged magma into subvolcanic chambers. Deposits of this type, if they occur in the Fox River Belt, would be hosted by the differentiated intrusions, likely forming basal accumulations.

The proposed model relating magmatism to volcanism in the Fox River Belt might preclude nickel sulphides from being associated with the lava flows, since immiscible sulphide would settle rapidly while the liquid was undergoing fractional crystallization in the chamber. If small cycles within the dunite layers existed and if they were of short duration, some immiscible sulphide might have been expelled from the chamber upon magma replenishment. An observation pertinent to the discussion of sulphide concentration in the lava, concerns the association of increasing sulphide abundance with increasing abundance of cumulus clinopyroxene in lower central layered zone and upper central layered zone rocks of the Fox River Sill (Scoates, in prep.). This association may reflect decreasing sulphur solubility with increasing fractional crystallization of olivine such that insolubility of sulphur is achieved upon clinopyroxene becoming a liquidus phase. If such a liquid were to be replaced and reach the surface, sulphur might still be insoluble and sulphide minerals could continue to precipitate. According to the proposed model, however, the base of the Fox River Sill and/or the base of the Lower differentiated intrusions would have the greatest potential for concentrations of primary immiscible sulphide.

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